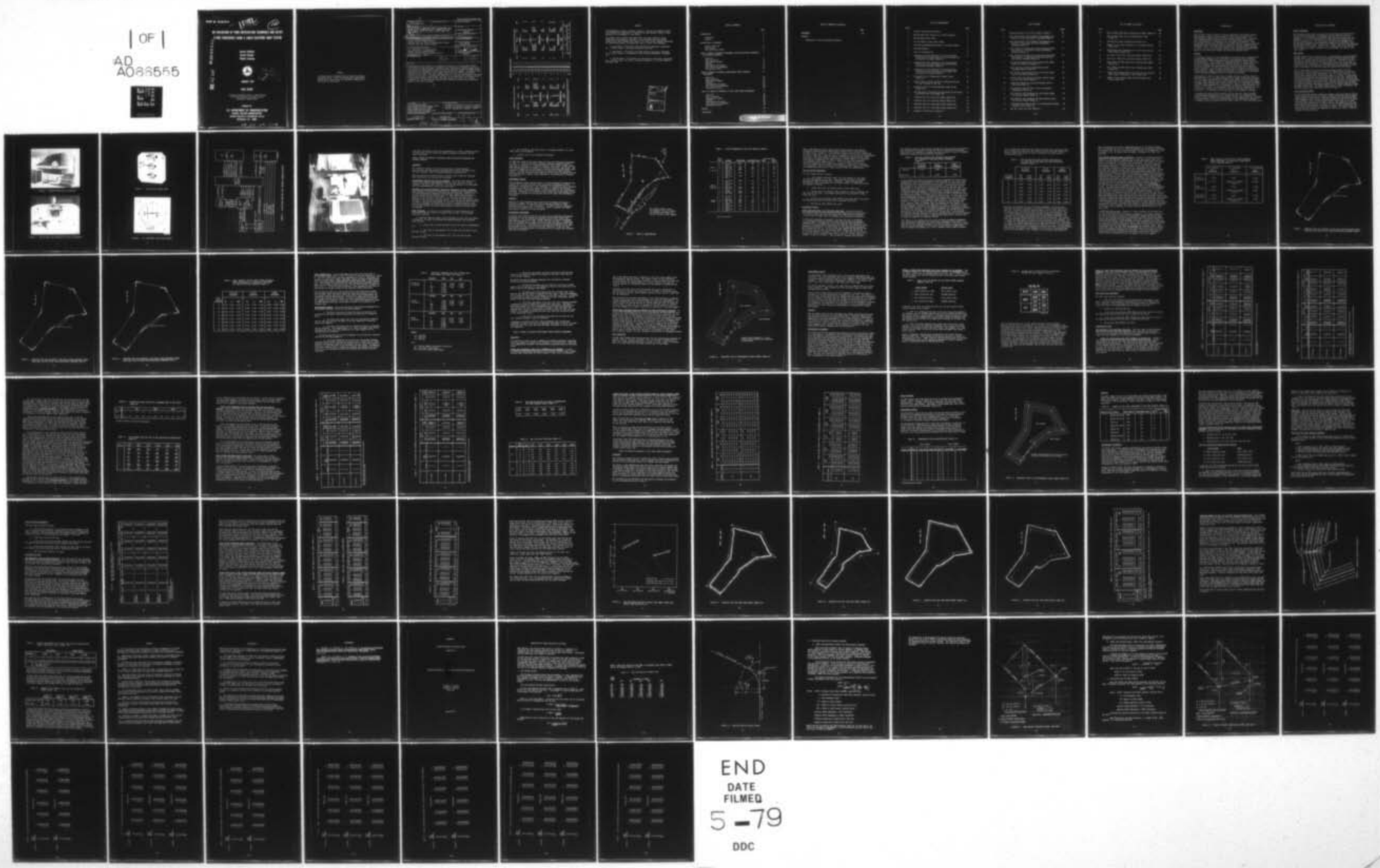
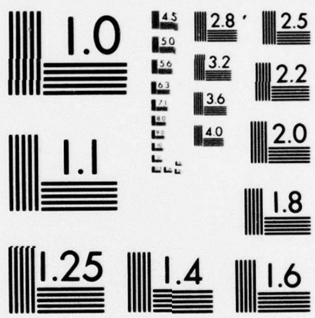
AD-A066 555 NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER ATL--ETC F/G 17/7
AN EVALUATION OF TURN ANTICIPATION TECHNIQUES AND OFFSET FLYING--ETC(U)
JAN 79 B GOLDBERG, D ELDREDGE, W CRIMBRING

UNCLASSIFIED FAA-NA-78-41 FAA-RD-78-114 NL

1 OF 1
AD
A066555



END
DATE
FILMED
5-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

REPORT NO. FAA-RD-78-114

AN EVALUATION OF TURN ANTICIPATION TECHNIQUES AND OFFSET FLYING PROCEDURES USING A SINGLE-WAYPOINT RNAV SYSTEM

Bernard Goldberg
Donald Eldredge
William Crimbring

JANUARY 1979

FINAL REPORT

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

19

1. Report No. 18 FAA-RD-78-114

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle 6

AN EVALUATION OF TURN ANTICIPATION TECHNIQUES AND OFFSET FLYING PROCEDURES USING A SINGLE-WAYPOINT RNAV SYSTEM.

5. Report Date

6. Performing Organization Code
ANA-200

7. Author(s)
10 Bernard Goldberg, Donald Eldredge, William Crimbring

8. Performing Organization Report No.
14 FAA-NA-78-41

9. Performing Organization Name and Address
Federal Aviation Administration
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
044-326-350

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D.C. 20590

13. Type of Report and Period Covered
9 Final rept.
May [redacted] - Nov [redacted]77

14. Sponsoring Agency Code
ARD-333

15. Supplementary Notes

11 Jan 79 12 89p.

16. Abstract

The purpose of this report is to document the results of a three-phased cockpit simulation which was conducted to evaluate turn anticipation techniques applicable for use with a single-waypoint, general aviation type area navigation (RNAV) system. Techniques were evaluated for both centerline and offset tracking. Performance was measured for two variables: total system crosstrack error (TSCT), and flight technical error (FTE). The major findings were: (1) all turn anticipation techniques tested could be used for centerline tracking; (2) no significant differences could be discovered between offset steady state and offset turn data; (3) a useable technique for turn anticipation during offset tracking is complex and contributes greatly to the pilot workload.

17. Key Words
Area Navigation (RNAV)
Total System Crosstrack Error (TSCT)
Flight Technical Error (FTE)
Omni Bearing Selector (OBS)
Course Deviation Indicator (CDI)
Distance to Waypoint (DTW)

18. Distribution Statement
Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	86	

METRIC CONVERSION FACTORS

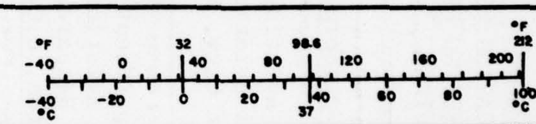
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

Acknowledgement is given to Messrs. Douglas A. Elliott and Joseph E. McCall who developed the equations for computing turn anticipation distance values presented in the appendix to this report.

The authors wish to advise the reader that this final technical report summarizes the information contained in the following data and interim reports which were prepared and issued as the work on this program progressed. For additional details, the reader may wish to consult the following:

1. Data Report -- "Procedural Turn Anticipation Techniques, Experiment No. 2, GAT-2A, Phase I--On-course Tracking," July 1977.

2. Data Report -- "Procedural Turn Anticipation Techniques, Experiment No. 2, GAT-2A, Phase II--Preliminary Offset Tracking Procedures," November 1977.

3. Interim Report -- "Procedural Turn Anticipation Techniques, Experiment No. 2, GAT-2A, Phase III--Offset Tracking Procedures--2- and 4-nmi Offsets," September 1978.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (Continued)

INTRODUCTION

BACKGROUND.

This activity is one of several projects conducted by the Federal Aviation Administration (FAA) in order to assist in the orderly introduction of Area Navigation (RNAV) into the National Airspace System (NAS). This final report summarizes and analyzes the data from three separate experiments which were conducted to investigate turn anticipation procedures. This three-phased activity was conducted at the FAA's National Aviation Facilities Experimental Center's (NAFEC) Cockpit Simulation Facility between May and November of 1977. The first phase examined turn techniques while operating on course. Phase II investigated various offset tracking procedures while phase III was conducted to expand the offset tracking data base.

PURPOSE.

The purpose of phase I of this experiment was to obtain pilot tracking data on three RNAV procedural turn anticipation techniques using the General Aviation Trainer (GAT)-2A equipped with a King (KNC-610) single-waypoint analog RNAV unit. Since Federal Air Regulations (FAR's) require that pilots be able to execute turns within the protected airspace at airway intersections, techniques for anticipating and executing turns were evaluated during this phase. All data were collected while navigating oncourse (i.e., with no offset). Phase I provided baseline data for three turn anticipation techniques which formed the basis for selecting one technique for measuring offset tracking performance during the follow-on activities.

The purposes of phase II were: (1) to develop and test a specific logic to determine when to set the Omni Bearing Selector (OBS) during offset tracking, (2) to evaluate the feasibility of using pilot judgment of Course Deviation Indicator (CDI) distance (and/or rate of movement) to transition from segment to segment while maintaining a desired offset, and (3) to determine the feasibility of using computed values of Distance to Waypoint (DTW) distances calculated on the basis of true airspeed (TAS) and the turn's magnitude for turn anticipation. Tables were constructed using an algorithm which has the capability to be implemented as an automated turn anticipation technique.

The purpose of phase III was to expand the data base for offset tracking which was begun in phase II and to evaluate the use of a noncentered CDI needle to fly to and maintain 2-and 4-nautical mile (nmi) offsets in a terminal area environment. Prior to collecting data, it was necessary to develop a technique to permit transition from an offset course to a final approach course.

DESCRIPTION OF EQUIPMENT

COCKPIT SIMULATOR.

All testing was done using the Singer-Link GAT-2A/Xerox XDS-530A computer facility which represented a twin-engine, general aviation aircraft (figure 1). This facility and equipment were the same as those used in experiment No. 1 of this series which is described in FAA Report No. FAA-RD-78-27 (reference 1). For these tests, the GAT-2A was equipped with conventional instruments, dual Navigation/Communication (NAV/COM), King KNC-610 RNAV computer, and a standard CDI. Figure 2 shows how this equipment was installed in the GAT-2A. Figure 3 is a closeup view of the KNC-610 control head while figure 4 depicts the CDI instrument and shows a 4-nmi right offset.

RNAV SYSTEM.

The RNAV system used in these tests was a single-waypoint, station-oriented computer which, in effect, moved the very high frequency omnirange (VOR) position to a phantom location called a "waypoint." The desired course to the waypoint was set with the OBS control knob on the CDI as is done in conventional VOR navigation. A corresponding course error signal was then shown on the CDI. The magnitude of the deviation was represented in miles rather than degrees (°) as is the case with conventional VOR system.

The CDI needle used in these tests moved through a range of ±5 dots (±5/8 inch). When operating in the en route ("RNAV") mode, the distance between each dot (1/8 inch) represented 1 mile of course deviation. In the approach ("APPR") mode, each dot was equal to 1/4 mile. A sine/cosine resolution potentiometer was incorporated into the CDI which permitted the accurate measurement of the OBS settings made by the pilots. Aircraft DTW was displayed directly on the RNAV unit. Waypoint selection was accomplished by tuning the number 2 NAV unit to the proper VOR frequency and entering the proper range (rho) and bearing (theta) for the desired waypoint through the RNAV control head. The GAT-2A, RNAV computer, flight instruments, and XDS-530A computer were interfaced as shown in figure 5.

DATA COLLECTION SYSTEM.

The Xerox XDS-530A computer (figure 6) software interfaced with the GAT-2A cockpit simulator and read into computer memory analog and digital signals using analog-to-digital (A/D) conversion equipment and direct input/output (DIO) equipment. The data were collected on magnetic tape with a 1-second clock interrupt used to control system timing. The format on the data collection tape consisted of a header record at the beginning of the tape and sequential data records, one record for each second of simulation run time. Both record types were 180 words in length. The header record was created from card input at the beginning of each run in order to identify the data at reduction time.

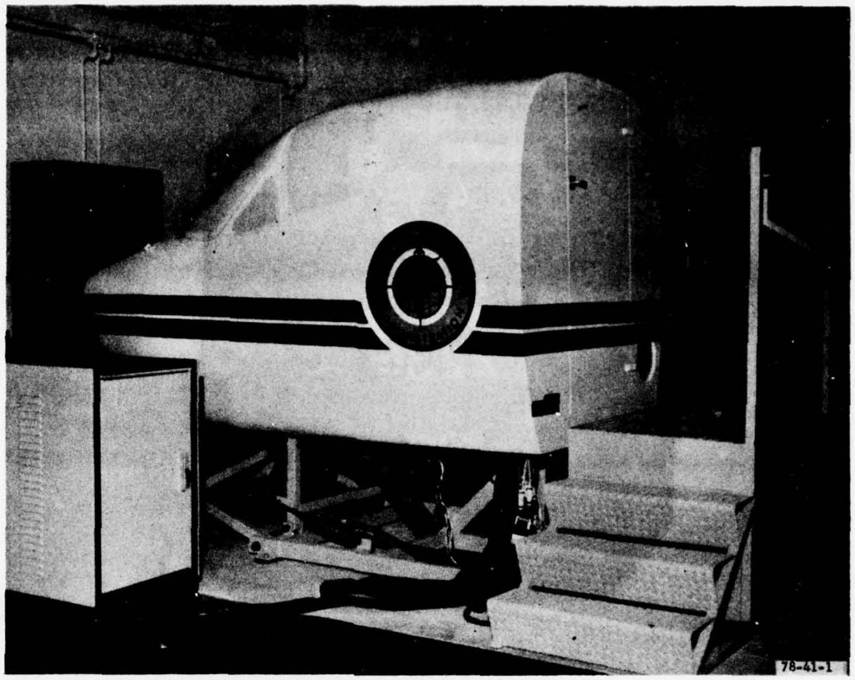


FIGURE 1. EXTERIOR VIEW--GAT-2A SIMULATOR

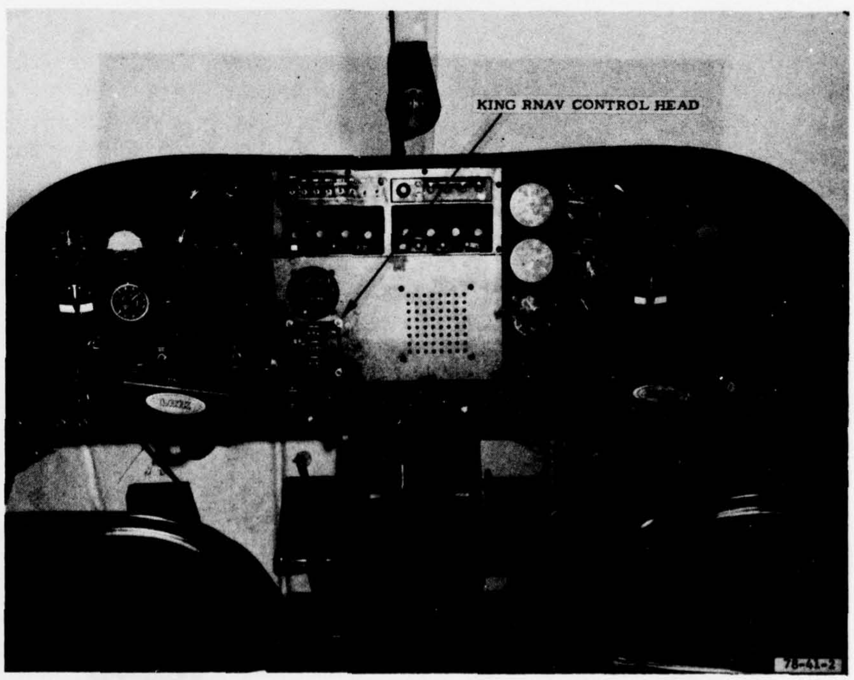


FIGURE 2. KNC-610 RNAV UNIT INSTALLED IN A GAT-2A SIMULATOR

FIGURE 3. KNC-610 RNAV CONTROL HEAD

FIGURE 4. CDI INSTRUMENT (4-NMI RIGHT OFFSET)

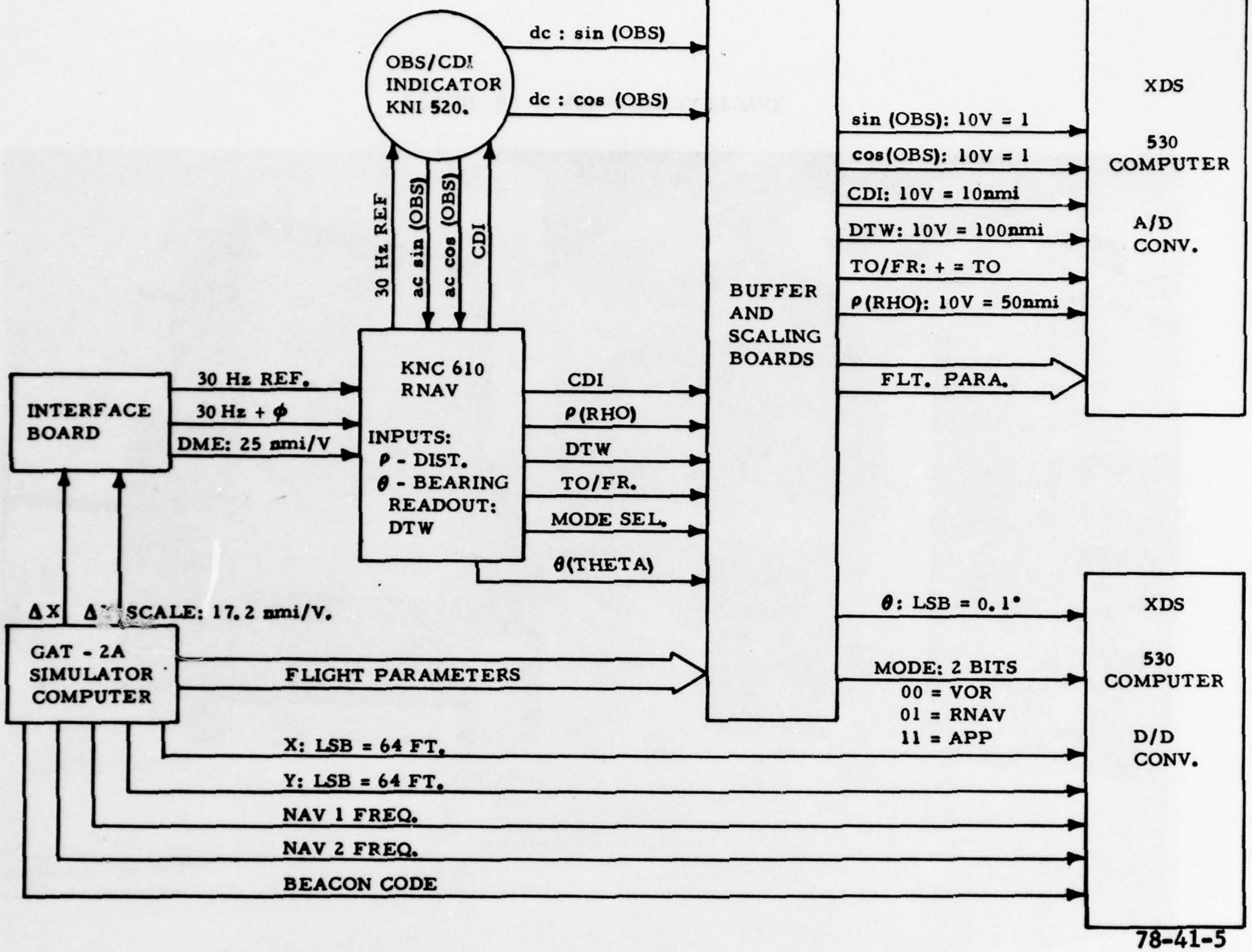


FIGURE 5. GAT-2A/KING RNAV/XDS-530A COMPUTER INTERFACE DIAGRAM

FIGURE 6.   XDS-530A COMPUTER

Each data item within a record was represented by a 16-bit, fixed-point word recorded from raw-form analog and digital voltages as acquired from the GAT-2A interfaces.

PHASE I METHOD OF APPROACH (PROCEDURAL TURN ANTICIPATION TECHNIQUES FOR ONCOURSE TRACKING

OBJECTIVE.

The objective of phase I of this activity was to collect baseline data on three turn anticipation techniques and to select one which could be used to measure offset tracking performance during phase II.

Data was collected on pilots flying a specific route using the following three procedural turn anticipation techniques.

FAA ADVISORY CIRCULAR (AC) 90-45A TECHNIQUE. The pilots were expected to "lead" their turns by approximately 1 mile for each 100 knots of true airspeed. The pilots were required to use the DTW display on the King RNAV unit for determining the actual turn start point.

UNIVERSITY OF ILLINOIS/CHAMPLAIN TECHNOLOGY INDUSTRIES (UI/CTI) TECHNIQUE. This technique is outlined in FAA Report No. FAA-RD-76-99, "Simulator Tests of Pilot Performance in Terminal Area Navigation Operations: Effects of Various Airborne System Characteristics." This method required pilots to monitor the DTW until the 2-nmi point. At this time, the pilots were expected to set the OBS to the next course. Once the OBS had been set, the airspeed of the aircraft determined the rate at which the CDI needle returned to center. The pilots were required to use their judgment (based on the rate of CDI movement) to initiate their turns. As the aircraft was turned onto the next course, the pilots were required to follow the needle until it centered.

NAFEC TECHNIQUE. In order to try this method of turn anticipation, the pilots were required to monitor airspeed, DTW, and CDI. The following steps were involved:

1. Calculate TAS and compute the CDI distance at which the turn should be initiated. In order to calculate the desired distance, the following logic was used.

a. Use 0.5 nmi for each 100 knots of TAS for turns of approximately 90°.

b. For turns of approximately 60° or less, use 0.25 nmi for each 100 knots of TAS.

c. For turns of approximately 120°, use 0.75 nmi for each 100 knots of TAS.

2. Set the OBS for the next course at a distance between 2 to 3 nmi (DTW) prior to the waypoint.

3. Initiate turn at the computed CDI distance.

ROUTE STRUCTURE.

All RNAV data flights were flown using the route B1 configuration presented in figure 7. Route B1 provided a Standard Instrument Departure (SID), a route leg to transition to a Standard Terminal Arrival Route (STAR), and an RNAV approach procedure to runway 4 at Atlantic City (ACY), New Jersey. The route B1 configuration has been used in previous simulation and flight tests conducted at NAFEC and at the University of Illinois for RNAV baseline studies. The data obtained from flying this route can be correlated with the data obtained from a similar study conducted at the University of Illinois (reference 2).

EXPERIMENTAL DESIGN.

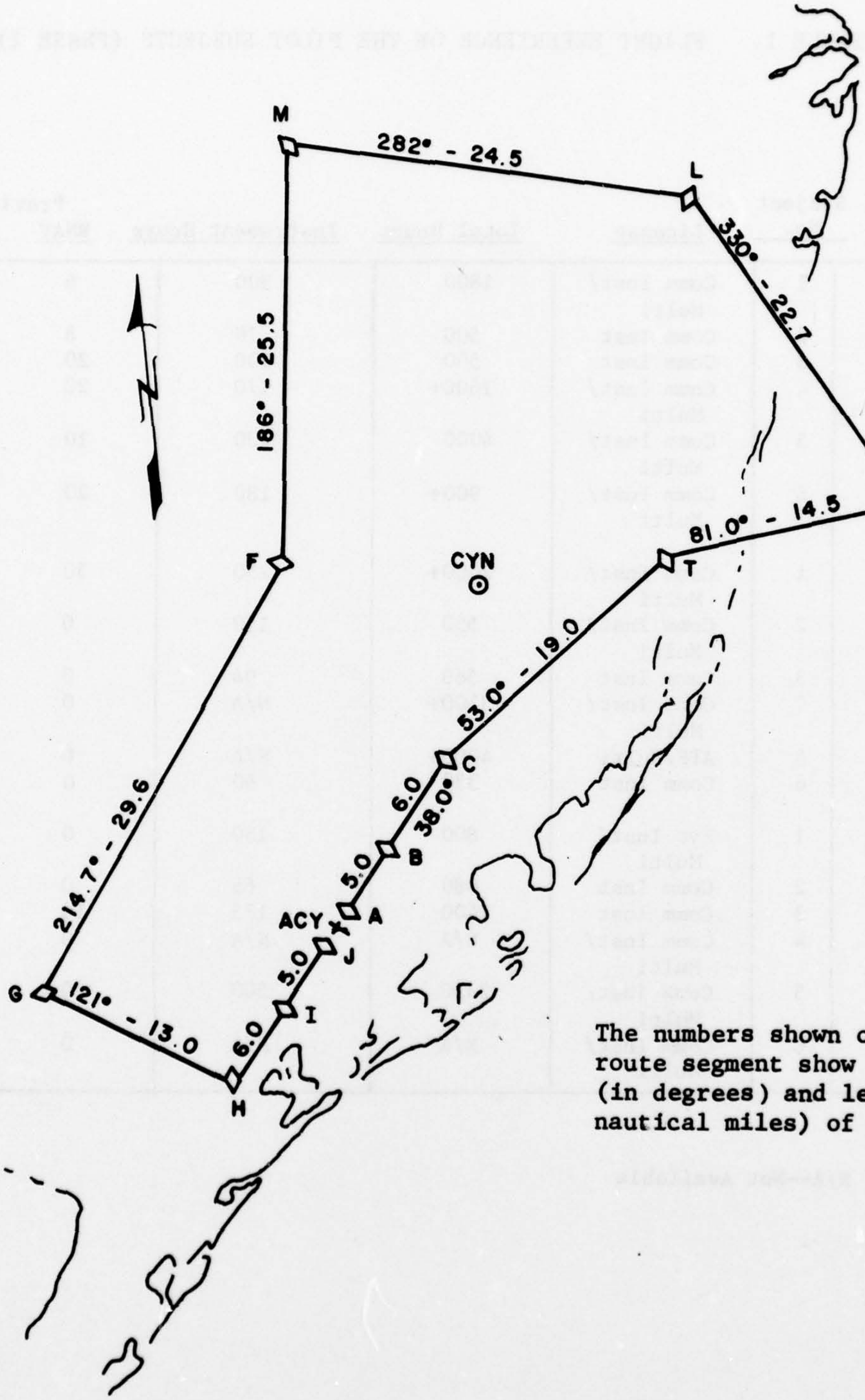
The experimental design used for phase I of this experiment was based on the premise that the three different turn anticipation techniques could be evaluated by assigning each of the techniques to a separate group of subjects. Assignments were made in this manner in order to minimize the confusion resulting from an individual having to learn more than one turn anticipation technique. Therefore, the 18 subjects were divided into three groups of six. Each group was assigned to perform only one of the three turn anticipation techniques.

SUBJECTS.

Subjects for this experiment were chosen from instrument-rated pilots available at NAFEC. The 18 pilots who participated ranged in flight experience from 350 to 7,400 total hours. The subject pilots' experience with the GAT-2 ranged from 0 to 100 hours. Table 1 presents the flight experience in hours for the pilot subjects.

EXPERIMENTAL PROCEDURES.

All pilots were given written and oral instructions regarding experimental objectives, use of the navigation equipment, and specific flight task requirements. The instructions stressed adherence to specific airspeeds which were designated for climb, cruise, and final approach. In addition, the route geometry was discussed and route charts and approach plates were given to the pilots. The specific turn anticipation technique to be used was explained in detail and the pilots were instructed to use the turn anticipation technique exactly as specified and not to modify the technique under any circumstance.



The numbers shown on each route segment show the heading (in degrees) and length (in nautical miles) of that segment.

FIGURE 7. ROUTE B1 CONFIGURATION

TABLE 1. FLIGHT EXPERIENCE OF THE PILOT SUBJECTS (PHASE I)

	Subject No.	License	Total Hours	Instrument Hours	Previous Hours RNAV	Previous Hours GAT-2
GROUP 1 AC 90-45A	1	Comm Inst/ Multi	1800	300	6	40
	2	Comm Inst	500	70	8	30
	3	Comm Inst	500	200	20	50
	4	Comm Inst/ Multi	1600+	170	20	10
	5	Comm Inst/ Multi	4000	700	10	100
	6	Comm Inst/ Multi	900+	180	20	30
GROUP 2 Univ. of Ill./CTI	1	Comm Inst/ Multi	2000+	250	30	50
	2	Comm Inst/ Multi	550	150	0	0
	3	Comm Inst	560	94	0	0
	4	Comm Inst/ Multi	3100+	N/A	0	0
	5	ATP/Multi	4000+	N/A	0	0
	6	Comm Inst	350	60	0	0
Group 3 NAFEC	1	Pvt Inst/ Multi	800	150	0	0
	2	Comm Inst	980	65	0	40
	3	Comm Inst	7400	175	10	0
	4	Comm Inst/ Multi	N/A	N/A	0	0
	5	Comm Inst/ Multi	2350	500	0	0
	6	Comm Inst/ Multi	N/A	N/A	0	0

N/A--Not Available

After completing the initial training and briefing session, each subject was given a familiarization flight (using a route that was different from the data route). During the familiarization flight, the instructor interrupted as often as required in order to assist or explain the use of the turn anticipation technique. After completing the initial training and familiarization flight, each subject was given another familiarization flight (without the instructor interrupting or assisting) in order to assure that the pilot understood the technique and was indeed using it. If the instructor felt that an additional familiarization flight was necessary to reinforce the technique, it was provided. Upon completion of the familiarization flights, the subject was immediately given the data flight using the route B1 configuration.

DATA COLLECTION PARAMETERS.

The data items extracted included:

a. Total system crosstrack (TSCT) turn data related to the transition from one segment to the next. These data were defined by envelopes (± 2 and/or ± 4 nmi) before and after a waypoint. These envelopes were sufficiently large to encompass all activities related to transitioning from one segment to the next.

b. Steady state TSCT and flight technical error (FTE) data.

c. Actual start turn distance (DTW, Distance to Wayline (DWYLIN), and time) used by the pilot. The heading time history data was used to establish this point.

d. Actual turn end distance (DYW, DWYLIN, and time) used by the pilot. The heading time history data was used to establish this point.

e. OBS setting (DYW, DWYLIN, and time).

DISCUSSION OF DATA.

MANUAL DATA REDUCTION -- OBS SET/START TURN TIMES. The first level of data reduction was directed toward extracting operational data concerning the method by which the pilots performed their RNAV-related navigation tasks in order to comply with the assigned turn anticipation procedures.

The data were subjected to analyses of variance in order to determine if any systematic difference existed among the three turn anticipation techniques and if the magnitude of the turn angle affected the manner in which the turn anticipation techniques were utilized. The results of these analyses of variances for the main effect of turn anticipation technique are presented in table 2. It can be seen that significant differences did occur in the data for both the distance (DTW) at which the OBS was set ($F = 19.546$, degrees of freedom = 2 and 15, $p < 0.001$) and for the distance at which the pilots elected to start their turns ($F = 10.992$, degrees of freedom = 2 and 15, $p < 0.001$). Both the OBS set distance and the start

turn distance, however, were directly influenced by the particular instructions that were given to the pilots for each of the turn anticipation techniques, and as such it is necessary to analyze the data in detail in order to determine differences among the turn anticipation techniques.

TABLE 2. MEAN OBS SET/START TURN DISTANCES FROM WAYPOINT AS A FUNCTION OF TURN ANTICIPATION TECHNIQUE (PHASE I)

	AC 90-45A Technique	UI/CTI Technique	NAFEC Technique
OBS Set	1.440	1.998	2.798
Start Turn	1.714	0.762	0.914

On the average, the pilots using the AC 90-45A recommended turn anticipation technique set their OBS approximately at the same time, or just after, they initiated the turn to the new course, and not prior to the turn as they had been briefed in the instructions to the subjects. AC 90-45A does not give any guidance to the pilots as to when to set the OBS for the next leg; it assumes that it is the pilot's responsibility to set the OBS at a point where it provides useful information concerning rate of closure to the new course in terms of CDI needle movement. For the UI/CTI and NAFEC-recommended turn anticipation procedures, the pilots set the OBS at points 1.236 nmi and 1.884 nmi, respectively, prior to initiating the required turn. In the case of the UI/CTI-recommended technique, the pilots were instructed to set the OBS at a point 2.0 nmi prior to the waypoint, using the DTW. The resultant average distance of 1.998 nmi indicates that they followed the instructions very well. However, there is evidence that this distance was not adequate for anticipating and starting the turn based on CDI motion. The pilots, in their informal comments, indicated that sufficient time was not available to sense the CDI motion correctly. For the NAFEC-recommended turn anticipation technique, the pilots were allowed to use a greater distance to set the OBS and were instructed to set the OBS at a point 2.0 to 3.0 nmi prior to the waypoint. The resultant average distance of 2.798 nmi indicates that the pilots recognized the need for more time in order to sense the CDI needle motion correctly and to apply the required turn distance formula.

From table 3 it is apparent that for both the UI/CTI-and NAFEC-recommended turn anticipation techniques, the pilots were influenced by the angle of the turn, and in fact used more distance in setting the OBS for larger turn angles. Based on the data presented in this table, it may further be conjectured that for larger turn angles (i.e., 120° or greater) and/or higher airspeeds

(i.e., greater than 200 knots TAS), greater distance (for setting the OBS) will be required in order that the pilots will have sufficient distance to correctly assess CDI motion in order to determine the proper place to initiate their turns.

TABLE 3. MEAN OBS SET/START TURN DISTANCES FROM WAYPOINT AS A FUNCTION OF TURN ANGLE AND TURN ANTICIPATION TECHNIQUE (PHASE I)

Turn Angle (Degrees)	AC 90-45A Technique		UI/CTI Technique		NAFEC Technique	
	OBS Set	Start Turn	OBS Set	Start Turn	OBS Set	Start Turn
15	1.533	1.333	2.017	0.233	2.217	1.217
28	1.967	1.833	1.700	0.033	2.717	0.067
111	1.533	1.900	2.183	1.233	3.067	1.350
48	1.900	1.783	1.800	0.867	2.633	0.850
96	1.700	1.767	2.367	1.033	3.100	0.933
29	1.567	1.667	1.633	0.767	2.900	1.083
93	0.117	1.667	2.283	1.167	2.950	0.900

The start turn distance for the AC 90-45A-recommended turn anticipation technique was based on computed true airspeed. Table 3 shows that for the most part, the pilots used the technique exactly as they were instructed. The average start turn distance was 1.714 nmi prior to the waypoint. The start turn distances for the UI/CTI-and NAFEC-recommended techniques were both based on CDI needle displacement and as such would be expected to be different from the distances used for the AC 90-45A technique. The average start turn distances were 0.762 nmi and 0.914 nmi prior to the waypoint. For the NAFEC turn anticipation procedure, the data indicate that the pilots did not follow the required procedure in that they were inconsistent on the smaller turn angles in terms of when they chose to make their turns. It would appear that the workload involved in computing the proper turn point for shallow-angle turns was not considered to be necessary by the pilots, or the method does not work for this type of turn. However, for turn angles approaching 90°,

the pilots appear to be able to understand the use of the proper distance. Table 3 indicates that for the UI/CTI-recommended turn anticipation technique, the distance used for start turn was directly related to the magnitude of the turn angle (i.e., the greater the turn angle, the greater the start turn distance).

TOTAL SYSTEM CROSSTRACK ERROR -- TURN DATA. Analyses of variance tests were completed on the mean ($\bar{X}$), variance (σ), and root mean square (RMS) total system crosstrack error statistics based on the time series data from 4.0 nmi prior to the waypoint to 4.0 nmi after the waypoint. The results of these analyses of variance for the main effects of turn anticipation technique are presented in table 4. From this table it can been seen that the mean total system crosstrack error data were not significantly different from each other even though the mean total system crosstrack error ranged between 0.028 nmi and 0.150 nmi for the three turn anticipation techniques. The variance and the RMS data, however, both resulted in significant differences being determined. In both cases, the AC 90-45A-recommended turn anticipation technique was significantly more variable (in terms of total system cross-track error) than either of the other two turn anticpation techniques. This finding indicates that the required turn distance (for most turn angles) is too large and as such introduces a greater amount of variability into the tracking data due to the fact that the pilots significantly undershoot the turn and must initiate additional turns in order to reach the desired course. The additional variability associated with the AC 90-45A-recommended turn anticipation technique was influenced almost entirely by the procedure which the pilot elected to use to return to the desired course. In the instructions to the subjects, the pilots were told to "continue turn until on next leg heading, then if you need to correct to get back on course, do so." These instruction were given specifically to insure that the pilots did use the AC 90-45A technique in order that the technique could be evaluated. Under actual Instrument Flight Rules (IFR) conditions, the pilots probably would have been cross-checking the CDI needle movement and would not have completed the turn at the specified point, but would have elected to continue flying on the present heading until the CDI needle would have started to give guidance with respect to the next course, assuming, of course, that the OBS had been set to the next course.

PLOTTED TURN DATA ($\pm$4 nmi). Figures 8, 9, and 10 present the $\pm$4.0-nmi data for each of the three turn anticipation techniques. Each figure consists of the six pilots' data for each of the techniques. These figures show that each of the techniques resulted in reasonably consistent on-course tracking during the transition from one segment to the next. The data in figure 8, the AC 90-45A technique, however, showed the most variability due to the fact that the pilots started their turns earlier than necessary and in the process of transitioning from one segment to the next had to correct back to the course due to the fact that they had undershot the intended course. Table 5 presents $\bar{X}$, sigma, and RMS total system crosstrack error data as a function of turn anticipation technique and turn angle. This table shows that turn angle as well as turn anticipation technique influenced the variability associated with transitioning from one segment to the next segment.

TABLE 4. MEAN, VARIANCE, AND RMS TOTAL SYSTEM CROSSTRACK ERROR (TURN DATA) AS A FUNCTION OF TURN ANTICIPATION TECHNIQUE (PHASE I)

	T.A. Technique No. 1 AC 90-45A	T.A. Technique No. 2 UI/CTI	T.A. Technique No. 3 NAFEC
$\overline{X}$ TSCT ($\pm$4.0 nmi)	0.028	0.083	0.150
	F = 2.733	Degrees of freedom = 2 and 15	P 0.096
TSCT ($\pm$4.0 nmi)	0.326	0.207	0.238
	F = 9.642	Degrees of freedom = 2 and 15	0.002
RMS TSCT ($\pm$4.0 nmi)	0.478	0.343	0.390
	F = 4.218	Degrees of freedom = 2 and 15	0.034

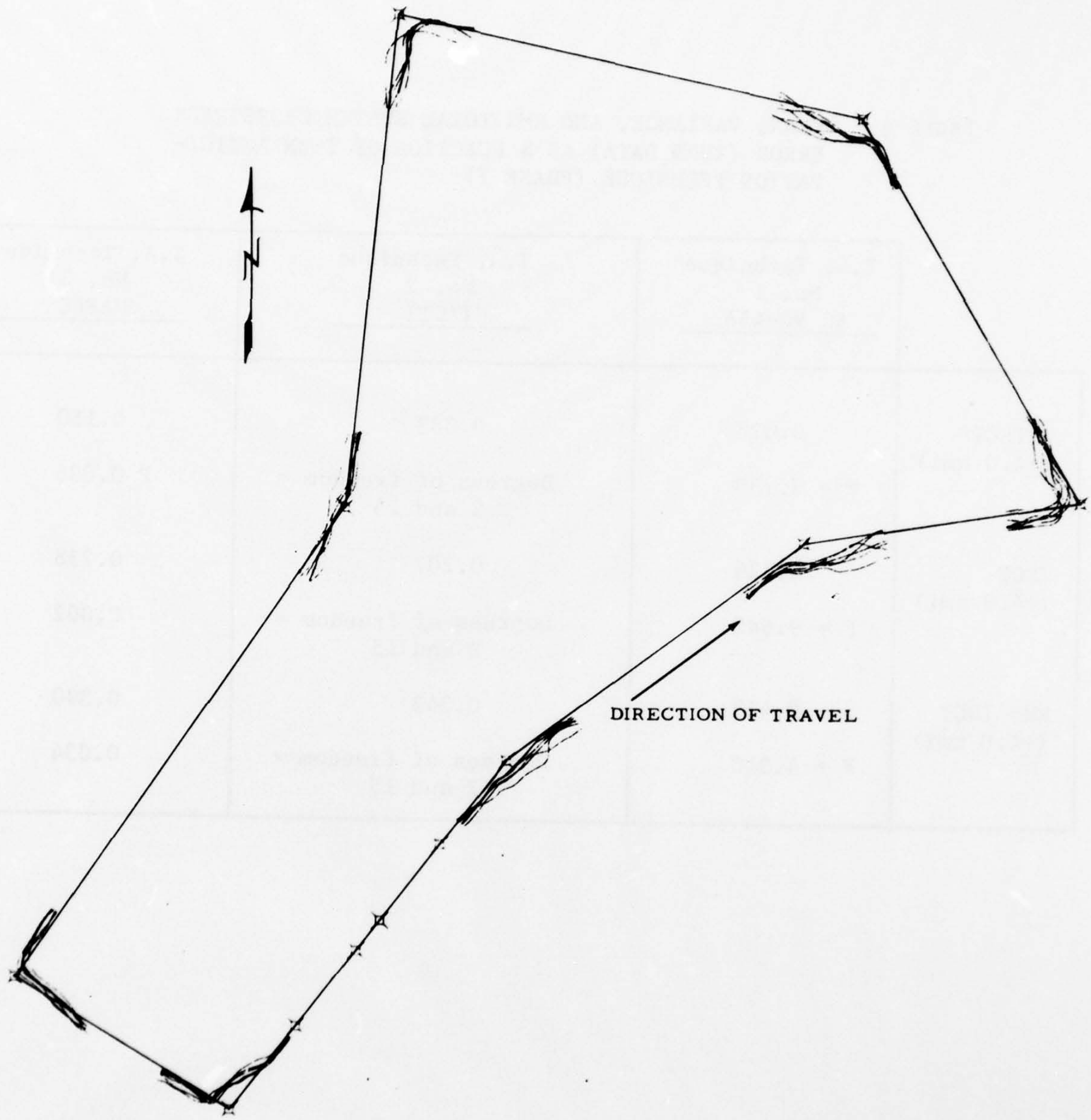


FIGURE 8. COMPOSITE PLOT (SIX SUBJECTS) OF THE TOTAL SYSTEM CROSSTRACK ERROR (TURN DATA) FOR THE AC 90-45A TURN ANTICIPATION TECHNIQUE (PHASE I)

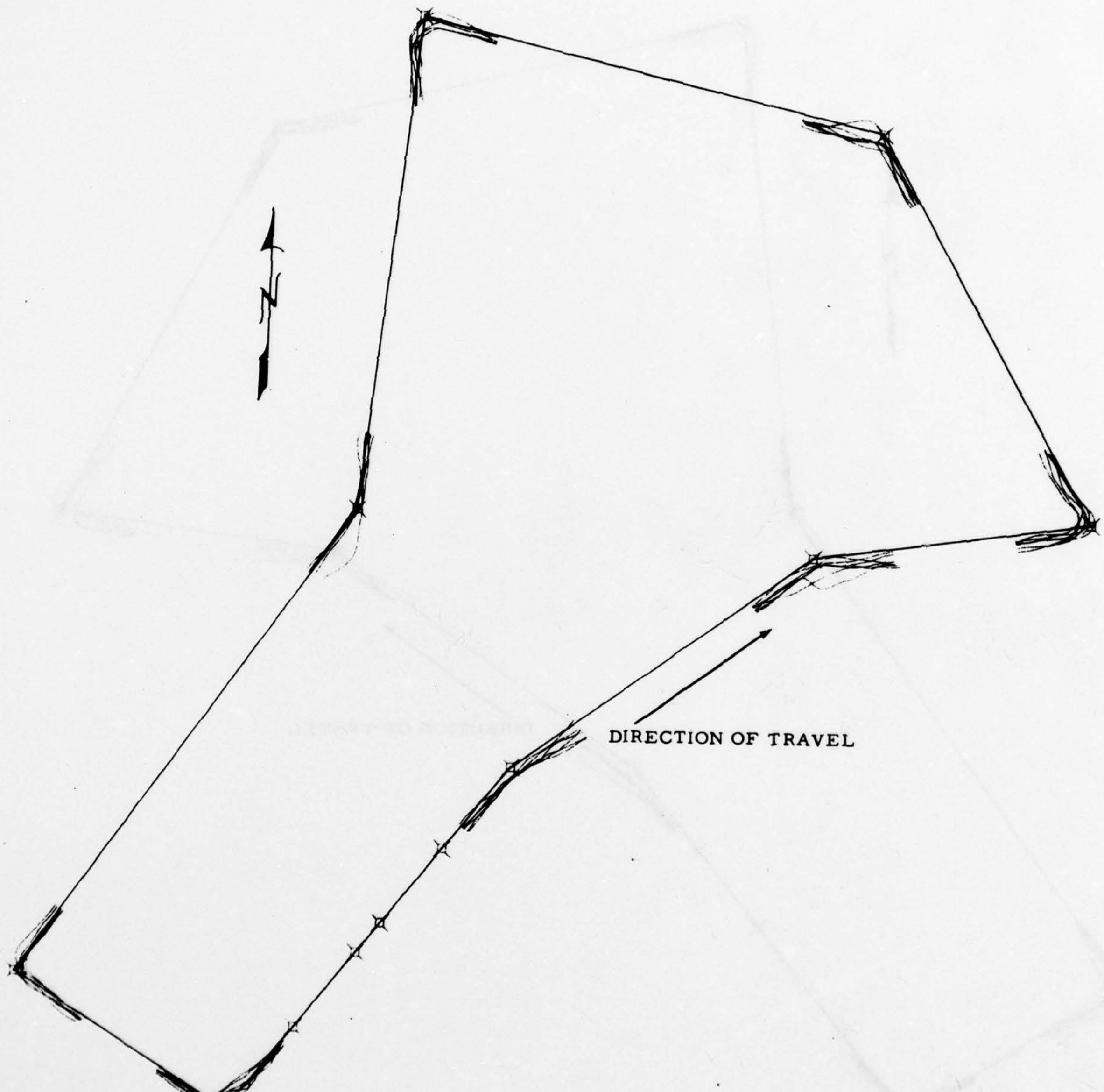


FIGURE 9. COMPOSITE PLOT (SIX SUBJECTS) OF THE TOTAL SYSTEM CROSSTRACK ERROR (TURN DATA) FOR THE UI/CTI TURN ANTICIPATION TECHNIQUE (PHASE I)

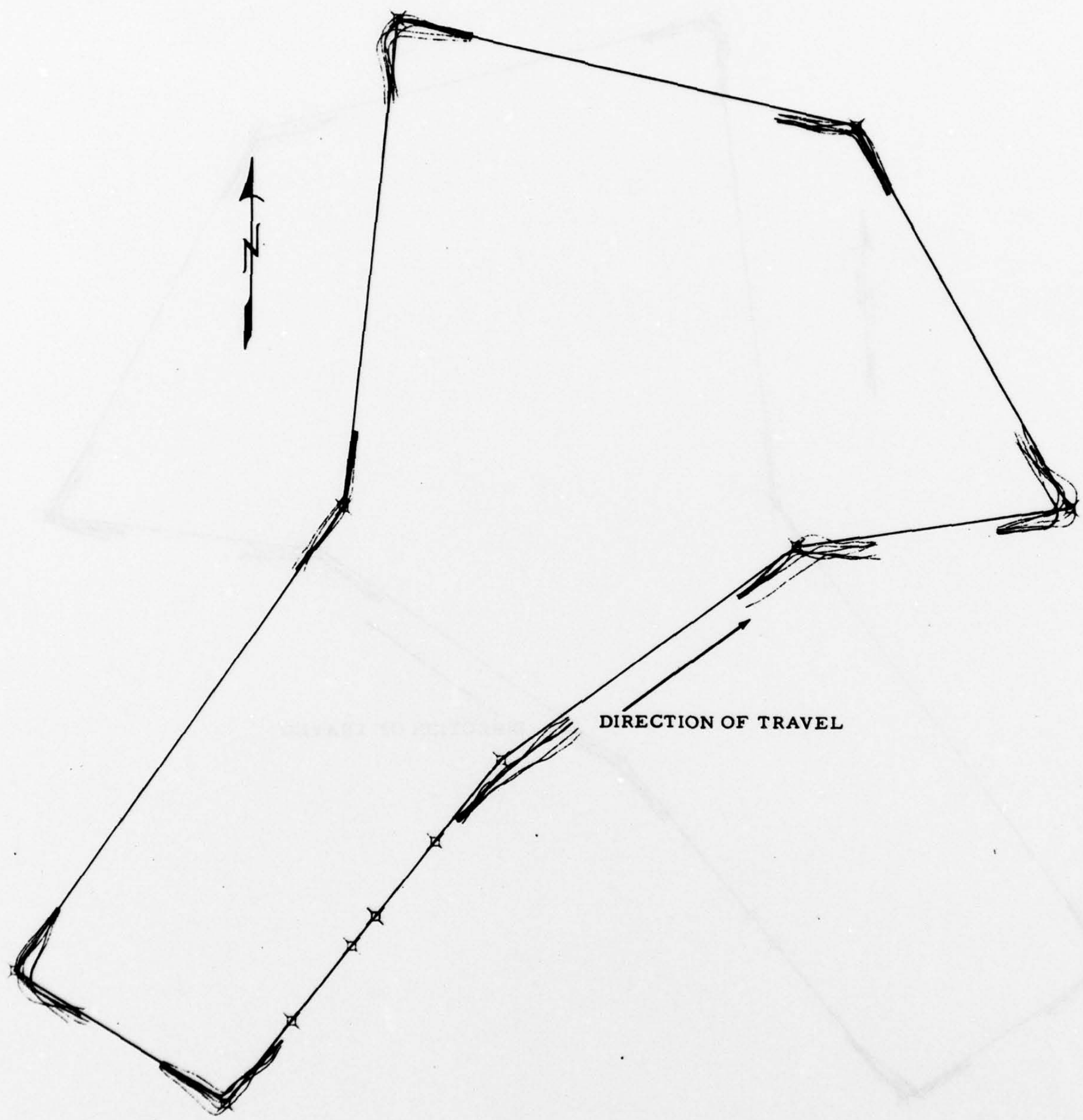


FIGURE 10. COMPOSITE PLOT (SIX SUBJECTS) OF THE TOTAL SYSTEM CROSSTRACK ERROR (TURN DATA) FOR THE NAFEC TURN ANTICIPATION TECHNIQUE (PHASE I)

TABLE 5. MEAN, VARIANCE, AND RMS TOTAL SYSTEM CROSSTRACK ERROR (TURN DATA) AS A FUNCTION OF TURN ANGLE AND TURN ANTICIPATION TECHNIQUE (PHASE I)

Turn Angle (Degrees)	AC 90-45A Technique			UI/CTI Technique			NAFEC Technique		
	$\overline{X}$	σ	RMS	$\overline{X}$	σ	RMS	$\overline{X}$	σ	RMS
15	0.437	0.198	0.481	0.214	0.144	0.326	0.589	0.209	0.628
28	0.724	0.342	0.804	0.284	0.195	0.399	0.479	0.227	0.558
111	-0.005	0.423	0.443	0.252	0.198	0.340	0.082	0.414	0.480
48	-0.492	0.397	0.640	0.056	0.190	0.531	-0.279	0.176	0.352
96	-0.314	0.323	0.458	0.058	0.341	0.352	0.106	0.276	0.330
29	-0.096	0.262	0.307	-0.171	0.153	0.255	-0.031	0.134	0.173
93	0.046	0.279	0.301	0.015	0.212	0.260	0.155	0.272	0.338
84	-0.075	0.383	0.393	-0.048	0.225	0.282	0.098	0.193	0.258

FINAL APPROACH DATA. In this experiment the pilots were instructed to use the RNAV approach mode (1 dot = 1/4 mile) for the final approach to runway 4. Data were collected on the final approaches in order to investigate the question of nonprecision (RNAV) approaches versus Instrument Landing System (ILS) approaches using a single-waypoint analog RNAV system in the terminal area. Even though the pilots flew the final approaches using RNAV approach mode, the pilots were also instructed to tune in the localizer frequency on NAV set No. 1. The CDI display for NAV No. 1 was covered in order that the pilot would not be able to see the CDI localizer needle deflections.

From the data in table 6 it can be seen that if the pilots had followed the ILS signal their approaches would have been more accurate in that the ILS localizer signal was more accurate in terms of mean displacement and variability than the RNAV guidance. However, the table data indicate that the 2-sigma variability was within the criteria established by AC 90-45A for terminal area guidance, and as such, the nonprecision approaches using the RNAV approach mode were sufficiently accurate to be useable in the terminal area.

QUESTIONNAIRE RESULTS. The pilots who used the AC 90-45A-recommended turn anticipation technique offered the following comments:

1. The pilots were aware of the fact that in using this turn anticipation technique, constant undershoots occurred due to turning too early.

2. The pilots were aware that this turn anticipation technique did not take into account the angle of the turn required to transition between two segments.

3. The pilots indicated that the workload involved in computing TAS was excessive. The inexperienced (i.e., lower instrument time) pilots indicated that they would have difficulty in a busy terminal area in implementing this procedure.

The pilots who used the UI/CTI-recommended turn anticipation technique offered the following comments:

1. The pilots expressed the concern that the distance between the point where the OBS had been set and the point at which the CDI needle movement had started to provide turn guidance was not sufficient, based on using the 2.0-nmi DTW point to set the OBS to the new course. Furthermore, the pilots indicated that at different airspeeds the problem would become worse (i.e., as airspeeds increase, the required lead distance must be increased).

TABLE 6. STATISTICAL SUMMARIES FOR FINAL APPROACH DATA (TSCT VERSUS FTE VERSUS ILS) (Phase I)

	Variable	TSCT	FTE	ILS
AC 90-45A Technique	$\bar{X}$	-0.005	0.066	-0.040
	σ	0.254	0.315	0.164
	RMS	0.271	0.341	0.182
	$\rho 1$	-0.794		
	$\rho 2$	0.823		
	$\rho 3$	-0.704		
	Variable	TSCT	FTE	ILS
UI/CTI Technique	$\bar{X}$	0.099	0.038	0.017
	σ	0.149	0.240	0.115
	RMS	0.195	0.195	0.145
	$\rho 1$	-0.630		
	$\rho 2$	0.860		
	$\rho 3$	-0.635		
	Variable	TSCT	FTE	ILS
NAFEC Technique	$\bar{X}$	0.142	-0.119	0.047
	σ	0.111	0.221	0.072
	RMS	0.184	0.254	0.084
	$\rho 1$	-0.462		
	$\rho 2$	0.883		
	$\rho 3$	-0.334		

Legend

$\rho 1$ = TSCT/FTE
$\rho 2$ = TSCT/ILS
$\rho 3$ = FTE/ILS

Note:

ρ = Product Moment Correlation Coefficient
FTE = CDI needle displacement
ILS = Localizer needle displacement

2. The pilots were aware that after setting the OBS they were using the CDI needle to measure the distance to the next course and not to the current waypoint.

The pilots who used the NAFEC-recommended turn anticipation technique offered the following comments:

1. The pilots were aware that the OBS had to be set at a point greater than 2.0 nmi prior to the waypoint in order to have sufficient lead time to use the CDI movement effectively.

2. The pilots were aware when using this technique that interpolation was required based on airspeed and turn angle. They also commented that in order for this type of technique to work, the rules had to be modified by interpolation based on external conditions of wind, turbulence, traffic density, and other workload-oriented problems.

3. The pilots were aware of the fact that this technique provided a guideline or place at which they could start their turn. (The basic difference between the UI/CTI-recommended turn anticipation technique and this technique was that for the UI/CTI technique, pilot experience and judgment were critical in determining the point at which to start the turn, whereas, in the NAFEC technique the start turn point was calculated based on the established rules.)

4. Only one of the six pilots indicated that he would not use this technique because it was too difficult.

In general, the pilots rated all three recommended turn anticipation techniques as being fairly easy to implement, and except in one or two cases indicated that they could and would use these techniques in flying under IFR conditions.

PHASE II METHOD OF APPROCH (PRELIMINARY OFFSET TRACKING PROCEDURES)

OBJECTIVE.

The objective of phase II was to examine two different methods of executing turns from segment to segment while tracking in the offset mode. There are two fundamentally different turn anticipation techniques which are described below:

OFFSET TURN TECHNIQUES USING PILOT JUDGEMENT OF CDI MOVEMENT. In order to define the methodology required to fly continuous offsets using a single-waypoint RNAV noncentered CDI needle system, it must first be determined

how to anticipate turns and to transition to the next course segment while maintaining the desired offset. The intent of phase II was, therefore, to establish an OBS setting logic and define a turn anticipation method that would be useable and understandable by the pilot while at the same time could be applied in a consistent manner for the purposes of separation and control.

Therefore, the first rule to be established dealt with a combination of two factors: (1) whether the offset was left or right of the parent course, and (2) whether the next course segment required a left turn or a right turn for the transition.

Once this protocol had been established, it was then necessary to formulate an OBS setting logic that would complement the transition requirements. The primary consideration which guided the OBS set logic was that the point (or time) at which the OBS was set had to provide sufficient time (or distance) for the pilot to sense the rate of movement of the CDI needle in order to apply his judgment as to when to initiate the transition to the next segment.

OFFSET TURN TECHNIQUES BASED ON COMPUTED DTW TURN ANTICIPATION DISTANCES. If the AC 90-45A-recommended method of turn anticipation had been selected to be utilized for offset tracking, the pilot would have had to calculate: (1) the angle of the turn, (2) the distance to the apex (of the offset) from the parent course, and (3) the geometry necessary to provide the proper DTW (miles) to start turn distance. All of these calculations are time consuming, require mental concentration by the pilot, and, therefore, would not be feasible for a single pilot operation in a busy terminal area unless it was an automated feature of the RNAV unit. Therefore, in order to implement an offset turn anticipation method based on DTW, it was necessary to consider the mathematics involved in the basic computations for an automated turn anticipation procedure, and to initiate the work outlined in the appendix of this report. This technique, however, was not intended for application in subsequent studies.

ROUTE STRUCTURE.

All RNAV data flights were flown using the route B1 configuration presented in figures 7 and 11. Route B1 provided a SID, a route leg to transition to a STAR, and an RNAV approach procedure to runway 4 at ACY. Figure 11 presents the 2-, 4-, and 5-mile left and right offsets used in this phase.

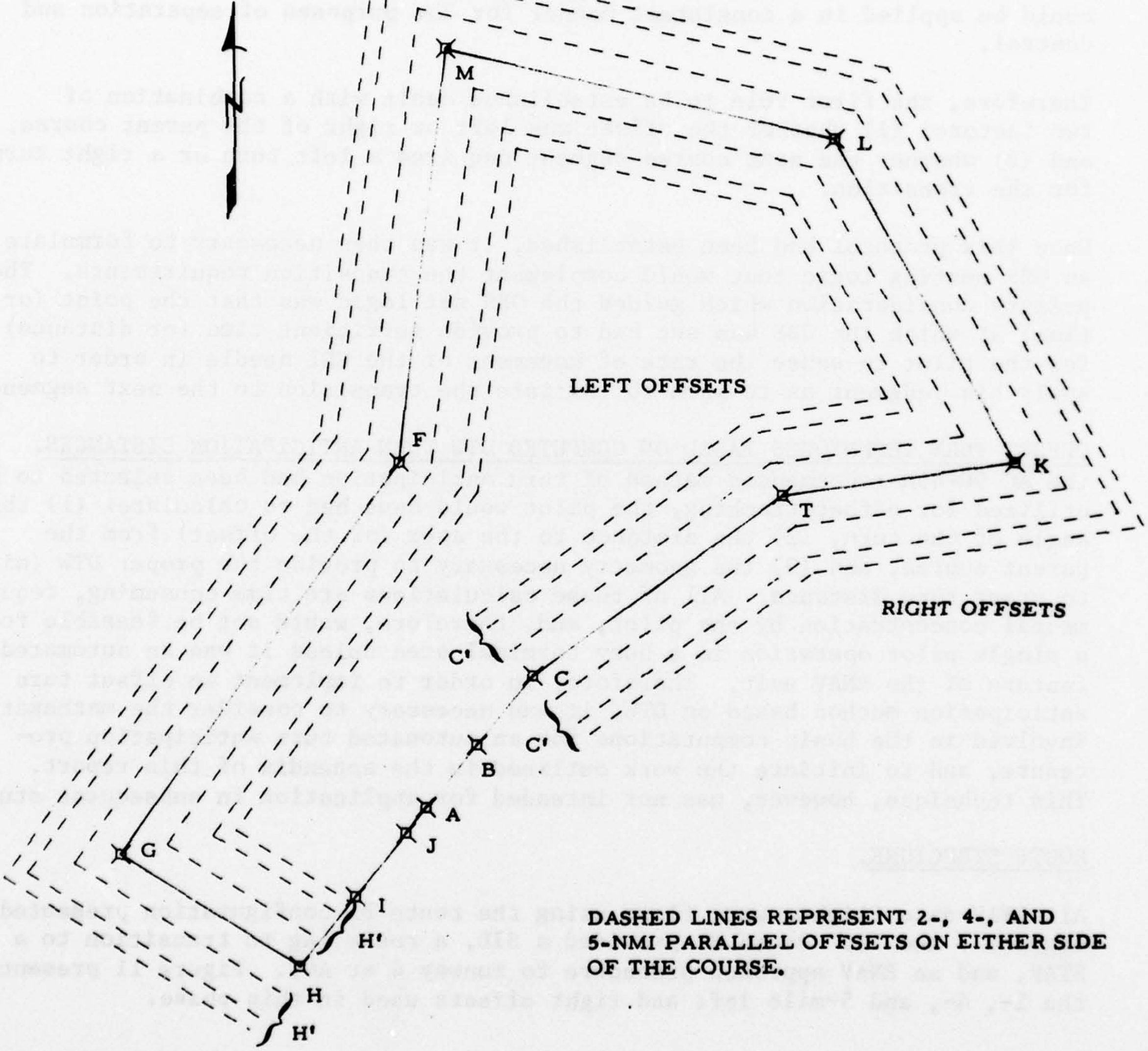


FIGURE 11. HORIZONTAL VIEW OF EXPERIMENTAL FLIGHT COURSES (PHASE II)

EXPERIMENTAL DESIGN.

For this phase II data collection effort, two separate experiments were conducted. The first experiment dealt with testing an OBS setting logic and a turn anticipation technique based on pilot judgment of CDI distance (and/or movement). This technique was evaluated for offsets of 2 nmi left, 4 nmi left, 5 nmi left, 2 nmi right, 4 nmi right, and 5 nmi right.

The second experiment tested a turn logic based on computed DTW turn anticipation distances. This technique was also evaluated using the same offset configurations as above.

The six offset flights which used pilot judgment of CDI distance (and/or movement) as the turn anticipation technique were run first. The second set of six offset flights which used the computed DTW turn anticipation distances were run second. No formal factorial design was established for this sequence of test runs since this test was not designed to distinguish which of the two methods of turn anticipation was the better, but was designed to evaluate the feasibility of using these two techniques for turn anticipation while maintaining an offset using the single-waypoint (noncentered CDI needle) RNAV system.

SUBJECTS.

The two subjects used in this experiment were highly experienced pilots who were the GAT-2 instructors for the RNAV project. These two subjects were used because this was an exploratory effort which required a high degree of competence in using the King RNAV unit in the GAT-2A simulator. It was not felt necessary to conduct a full-scale factorial experiment with additional subjects at this time to determine the feasibility of using either: (1) the pilot judgment of CDI distance (and/or movement) technique, or (2) the computed DTW distance technique for turn anticipation.

EXPERIMENTAL PROCEDURES.

The pilots were briefed regarding experimental objectives and specific flight task requirements. In addition, the route geometry was discussed and route charts and approach plates were given to the pilots. The OBS setting logic and the specific turn anticipation techniques to be used were explained in detail and the pilots were instructed to use the OBS set logic and turn anticipation techniques exactly as specified and not to modify the techniques under any circumstances. The pilots were instructed to begin flying the offset course after passing waypoint C. The procedure at this point was to establish a 45° intercept track and then transition to the offset course, then fly the constant offset until intercepting the final approach course. During the offset flight the pilot was expected to maintain an altitude of 12,000 feet and 160 knots indicated airspeed (i.e., approximately 195 knots TAS). The pilot was instructed to begin his descent to 2,000 feet at a point approximately 5 nmi beyond waypoint F.

METHOD I; OFFSET TURN TECHNIQUES USING PILOT JUDGMENT OF CDI MOVEMENT. This technique consisted of two distinct required actions: (1) implementation of the OBS set logic, and (2) implementation of the turn logic. Table 7 presents the basic logic to be used for setting the OBS to the next course during offset tracking.

TABLE 7. BASIC LOGIC FOR SETTING THE OBS DURING OFFSET TRACKING (PHASES II AND III)

Course Change	OBS Set Logic
a. Right offset/turn right	Twice offset value
b. Right offset/turn left	TO/FROM indicator
c. Left offset/turn left	Twice offset value
d. Left offset/turn right	TO/FROM indicator

In general, the rules for setting the OBS (for the next course) during offset tracking are as follows:

1. When on an offset and the next course turn occurs after passing the waypoint, use the TO/FROM indicator as a cue for setting the OBS to the next course (table 7, cases b and d). Therefore, when the aircraft crosses the wayline (a line perpendicular to the course through the waypoint) and the TO/FROM flag is neither TO nor FROM, but is "buried out of view," the OBS should be set.

2. When on an offset and the next course turn occurs prior to the waypoint, use a value (of distance to waypoint) that is twice the offset distance for setting the OBS to the next course. For example, if a 4-nmi offset is being flown, the OBS will be set when DTW reads 8 nmi (table 7, cases a and c).

Figure 12 presents a placard which is mounted in the cockpit directly above the RNAV unit. This placard can be used by the pilot to assist in applying rules 1 and 2. These rules for the OBS setting logic were derived by experimentation and actual testing and appeared to offer a reliable means of establishing when the OBS should be set.

FIGURE 12. PLACARD USED TO ASSIST THE PILOT IN APPLYING THE OBS SET LOGIC (PHASES II and III)

FOR OBS SET

OFFSET	TURN	LOGIC
RIGHT	RIGHT	DTW
	LEFT	T/F
LEFT	LEFT	DTW
	RIGHT	T/F

78-41-12

Once the OBS has been set, the CDI needle will move from its present position and will either be pegged (at the extremes of the display) or will move toward the center of the display, except when using the TO/FROM indicator on shallow angle turns (then it will either move very little or not at all). The pilot will continue to maintain his present heading until the CDI needle approaches the desired offset distance. As the CDI needle approaches the desired offset distance, the pilot will have to use his judgment based on the CDI distance (and/or rate of movement) to initiate his turn to the next course. As the aircraft is turning onto the next course, the pilot will monitor the CDI needle until it reaches the desired offset distance. Pilots are expected to turn at a rate not to exceed 3° per second (i.e., standard rate turn). The pilot should bear in mind that the faster the airspeed, the faster the CDI movement, and the more the pilot will have to lead his turn.

METHOD 2; OFFSET TURN TECHNIQUES BASED ON COMPUTED DTW TURN ANTICIPATION DISTANCES. The pilot was instructed to use a turn anticipation technique based on tabled DTW distances. These distances were determined by the equations outlined in the appendix. The values derived from these equations were provided to the pilot on copies of the route B1 map. The pilot was expected to use the DTW values to initiate the transition from one segment to the next. Positive values of DTW distance represented a distance TO the offset wayline and negative values of DTW distances represented a distance FROM the offset wayline. In this experiment the pilots were requested to set the OBS after they had initiated the turn to the next leg. The reason for this was to insure that the pilots did indeed use the computed turn anticipation distance and were not influenced by CDI needle distance (and/or movement).

DATA COLLECTION PARAMETERS.

The data items extracted included:

a. TSCT turn data related to the transition from one segment to the next. These data were defined by envelopes (±2 and/or ±4 nmi) before and after a waypoint. These envelopes were sufficiently large to encompass all activities related to transitioning from one segment to the next.

b. Steady state TSCT and FTE data.

c. Actual start turn distance (DTW, DWYLIN, and time) used by the pilot. The heading time history data was used to establish this point.

d. Actual turn end distance (DTW, DWYLIN, and time) used by the pilot. The heading time history data was used to establish this point.

e. OBS setting (DTW, DWYLIN, and time).

DISCUSSION OF DATA.

DATA REDUCTION -- OBS SET/START TURN DATA. The first level of data reduction was directed toward extracting operational data concerning the method by which the pilots performed their RNAV-related navigation tasks in order to comply with the assigned turn anticipation procedure.

Offset Turn Techniques Using Pilot Judgment of CDI Movement. Tables 8 and 9 present the OBS setting times and distances (including DTW, and CDI displacement) and actual start turn times and distances (including DTW, DWYLIN, and CDI displacement). Also included in these tables are the position of the TO/FROM indicator and the magnitude of the turn angle. These data are from the runs which used pilot judgment of CDI distance (and/or rate of movement) for turn anticipation. Tables 12 and 13 present the same set of data from the runs which used the tabled values of DTW distances for turn anticipation.

TABLE 8. OBS SET/START TURN DISTANCES FOR LEFT OFFSETS USING THE CDI TURN METHOD (PHASE II)

				OBS Set				Turn Start					
	Waypoint	Turn Angle (Degrees)	OBS Logic	Start Time	DTW Dist.	CDI	TO/ FROM/ OFF	Start Time	DTW Dist.	Wayline Dist.	CDI	TO/ FROM/ OFF	Elapsed Time
2.0 nmi Left	T	28	1	0730	1.8	1.7	TO	0749	1.9	0.4	1.9	OFF	19
	K	111	2	1004	4.4	3.6	TO	1033	3.5	0.5	2.3	FROM	29
	L	48	2	1393	4.2	4.2	TO	1422	2.7	1.3	2.7	OFF	29
	M	96	2	1837	3.4	3.3	TO	1844	3.2	0.2	2.2	FROM	7
	F	29	1	2311	1.7	1.7	OFF	2317	1.9	(27.7)*	1.7	TO	4
	G	93	2	2771	4.3	3.8	TO	2795	3.5	0.6	2.8	FROM	24
4.0 nmi Left	T	28	1	0718	4.2	4.0	TO	0724	4.3	1.1	4.1	TO	6
	K	111	2	0914	8.6	6.0	TO	0932	7.9	1.3	5.5	FROM	18
	L	48	2	1214	4.9	5.0	OFF	1220	4.9	0.3	4.8	OFF	6
	M	96	2	1481	8.5	7.4	TO	1518	6.5	0.6	4.8	FROM	37
	F	29	1	1965	4.3	4.5	TO	1973	4.3	0.1	4.4	TO	8
	G	93	2	2339	9.2	8.4	OFF	2390	7.1	1.8	6.2	FROM	51
5.0 nmi Left	T	28	1	0770	5.4	5.5	TO	0784	5.6	1.1	5.5	TO	14
	K	111	2	0955	10.3	7.0	FROM	0978	9.5	1.2	6.2	FROM	23
	L	48	2	1127	10.2	10.2	TO	1233	6.4	(15.7)*	5.9	OFF	106
	M	96	2	1464	10.1	7.5	FROM	1500	8.7	(19.8)*	5.4	FROM	36
	F	29	1	1908	5.9	6.2	TO	1919	6.1	0.0	6.1	TO	11
	G	93	2	2305	9.0	7.3	FROM	2329	8.0	0.7	6.1	FROM	24

*The aircraft had passed the angle bisector and the value represented the distance TO the next wayline.

TABLE 9. OBS SET/START TURN DISTANCES FOR RIGHT OFFSETS USING THE CDI TURN METHOD (PHASE II)

				OBS Set				Turn Start					
	Waypoint	Turn Angle (Degrees)	OBS Logic	Start Time	DTW Dist.	CDI	TO/FROM/OFF	Start Time	DTW Dist.	Wayline Dist.	CDI	TO/FROM/OFF	Elapsed Time
2.0 nmi Right	T	28	2	0697	3.9	-3.6	TO	0761	2.8	(16.3)*	-2.4	OFF	64
	K	111	1	1038	1.9	-1.7	TO	1057	2.4	2.3	-0.7	TO	19
	L	48	1	1501	2.7	-2.3	TO	1507	2.7	(27.7)*	-2.5	TO	6
	M	96	1	1942	3.5**	-1.3	OFF	1947	3.5	0.4	-1.5	TO	5
	F	29	2	2332	2.9	-2.4	TO	2337	2.4	1.0	-2.3	TO	5
	G	93	1	2712	1.8	-0.6	TO	2721	2.1	1.3	-1.1	TO	9
4.0 nmi Right	T	28	2	0791	8.3	-7.5	TO	0927	5.2	(19.0)*	-5.0	OFF	136
	K	111	1	1232	4.5	1.1	TO	1370	8.1	0.4	-3.9	TO	138
	L	48	1	2011	4.9	-4.5	OFF	2023	5.2	(30.1)*	-5.2	TO	12
	M	96	1	2513	4.5	-1.3	OFF	2556	5.9	0.9	-3.5	TO	43
	F	29	2	3020	8.1	-7.1	TO	3126	4.6	(32.7)*	-4.6	OFF	106
	G	93	1	3682	4.2	0.1	TO	3751	5.5	1.0	-3.2	TO	69
5.0 nmi Right	T	28	2	0635	10.1	-9.0	TO	0771	5.2	1.1	-5.4	OFF	136
	K	111	1	1091	4.8	-1.3	TO	1207	7.2	2.5	-3.6	TO	116
	L	48	1	1789	5.4	-5.2	TO	1815	5.4	0.4	-5.0	TO	26
	M	96	1	2303	5.1	0.2	TO	2359	5.9	2.2	-3.1	TO	55
	F	29	2	2740	9.6	-8.5	TO	2814	5.8	2.3	-5.8	TO	74
	G	93	1	3222	5.2	0.1	TO	3264	6.0	2.5	-2.8	TO	42

* The aircraft had passed the angle bisector and the value represented the distance TO the next waypoint.

** Caused by RNAV system malfunction which resulted in an erroneous DTW reading.

For the most part, the pilot did apply the rules established for the OBS setting logic. Table 8 shows that for the left offsets, four of the six turns required that the OBS be set at a distance that was two times the offset value. From these data, it appears that the pilot did not have a problem with using the required rule. The other two turns (at waypoints T and F) required that the OBS be set upon noticeable movement of the TO/FROM indicator. It is evident that the required action resulted in OBS being set at a DTW distance equivalent to the offset distance, which in turn required the pilot to initiate the transition to the next segment almost immediately.

Table 9 data indicate that for the right offsets, four of the six turns required that the OBS be set upon noticeable movement of the TO/FROM indicator. From these data (except for one case which was affected by an RNAV system malfunction), it appears that the pilot did not have a problem with using the required rule. The other two turns (at waypoints T and F) required that the OBS be set at a distance that was two times the offset value. From the data in table 9, it can be seen that the required action was implemented at the desired DTW distance.

It is interesting to note the manner in which the CDI needle operates once the OBS has been set. The data in table 8 show that for those turns (i.e., left offsets) that required the OBS to be set at twice the distance of the offset (waypoints K, L, M, and G) the CDI needle would move to the right of the display (for 4-and 5-nmi offsets, essentially, the needle would be pegged at the extreme right of the display). As the aircraft approached the next course segment, the needle would move toward the appropriate distance (toward the center) and the pilot would initiate the turn based on his judgment of the needle movement. The five-dot limit of the CDI instrument caused a problem (with a noncentered needle) in that the pilot (for the 4- and 5-nmi offsets) could not perceive the needle movement until it was approximately 1 mile from the fifth dot, because the needle did not start to move until it was in the range from 6.4 to 6.1 nmi. Of course, this fact made the 5-nmi offset more difficult to fly since there was very little distance in which to sense the needle movement. In fact, at higher aircraft speeds than those used in this simulation (i.e., greater than 200 knots TAS), the 5-nmi offset would not be practical due to the five-dot limitation on the CDI instrument of only approximately 1-mile lead time between the pegged position and the fifth dot. In addition, the CDI instrument used in this study was not symmetric but had a bias toward the right side which affected the pilot's capability to minimize flight technical error during a left offset. Table 10 presents the calibration values for the CDI instrument used in this study. It can be seen that a bias was evident for the right needle deflection. The effect of this bias will be explored in relation to the steady state TSCT and FTE data later in this section.

Table 9 data indicate that for those turns (i.e., right offsets) that required the OBS to be set upon noticeable movement of the TO/FROM indicator (waypoints K, L, M, and G) the CDI needle would either move toward the center of the display or for the shallower angle turns (waypoint L) might not move

TABLE 10. CALIBRATION VALUES FOR THE CDI INSTRUMENT USED IN THIS STUDY (PHASE II)

	Left					Center	Right				
Dots	-5	-4	-3	-2	-1	0	1	2	3	4	5
Volts*	-5.25	-4.15	-3.06	-2.00	-1.03	0.010	1.00	1.99	3.10	4.30	5.65

*Voltage is equivalent to nautical mile displacement.

TABLE 11. DTW DISTANCES USED FOR TEST OF TURN ANTICIPATION COMPUTATIONS (PHASE II)

Waypoint	2.0 nmi left	4.0 nmi left	5.0 nmi left	2.0 nmi right	4.0 nmi right	5.0 nmi right
T	2.0 (FROM)	4.1 (FROM)	5.1 (FROM)	2.2 (TO)	4.2 (TO)	5.3 (TO)
K	5.0 (TO)	8.4 (TO)	10.4 (TO)	2.4 (FROM)	5.8 (FROM)	7.8 (FROM)
L	2.4 (TO)	4.5 (TO)	5.6 (TO)	2.0 (FROM)	4.2 (FROM)	5.2 (FROM)
M	3.9 (TO)	7.0 (TO)	7.9 (TO)	2.2 (FROM)	5.2 (FROM)	6.3 (FROM)
F	2.0 (FROM)	4.1 (FROM)	5.1 (FROM)	2.2 (TO)	4.2 (TO)	5.2 (TO)
G	3.7 (TO)	6.4 (TO)	7.9 (TO)	2.2 (FROM)	4.9 (FROM)	6.3 (FROM)

at all (especially if the aircraft was off course). As the aircraft approached the next course segment, the needle would move out (from the center) toward the appropriate distance and the pilot would initiate the turn based, once again, on his judgment of the needle movement.

Offset Turn Techniques Based On Computed DTW Turn Anticipation Distance. For the DTW-based turn anticipation method, the pilot was specifically requested not to set the OBS until after the turn had been initiated and he was established on the new heading. Therefore, the OBS setting logic was not applied and the OBS setting time and distance was not as critical, and, in fact, was not as necessary as it was for the CDI-based turn anticipation method. The data for the OBS setting times and distances, however, are presented in tables 11 and 12 in order to show the relationships between the start turn data and the OBS set data.

Table 11 presents the interpolated values of DTW distances and the status of the TO/FROM indicator used in this study to test the concept of using an automated turn anticipation method with a single-waypoint RNAV system. The interpolated values were calculated based on the tabled values presented in tables A-4 and A-5 of the appendix. Tables 12 and 13 present the start turn data derived from this study. The data in tables 11 and 12 indicate that, for the most part, the pilot did use the tabled values at the appropriate times. The effect of using both the CDI-based and DTW-based turn anticipation methods will be examined later in this section.

For the DTW method of turn anticipation, it was not possible for the pilot to intercept the final approach course using the values provided by the turn anticipation equations. Therefore, the pilot was provided with a set of DTW values at which point he was to set the OBS in order to intercept the final approach course. The OBS set values are presented in table 14. Once the OBS had been set at these points, the CDI needle movement was used to intercept the final approach course.

TOTAL SYSTEM CROSSTRACK ERROR -- TURN DATA. The second level of data reduction was directed toward measurement of crosstrack error for both of the turn anticipation systems tested. Table 15 presents the RMS statistics based on the time series data from 4 nmi prior to the waypoint to 4 nmi after the waypoint.

From the data in table 15, it can be seen that considerable variability existed in the turn data. For the CDI-based turn anticipation method, the shallow angle turn at waypoint F resulted in the greatest changes in variability during the 5-nmi offsets. In fact, for the 5-nmi right offset, the 2-RMS criteria of ± 2 nmi was exceeded. For the DTW-based turn anticipation method, the acute angle turn (111°) at waypoint K resulted in the greatest overall variability. The resultant variability for this acute angle transition may reflect a weakness in the algorithm used for the DTW distance computations, and, as such, should be evaluated further.

TABLE 12. OBS SET/START TURN DISTANCES FOR LEFT OFFSETS USING THE DTW TURN METHOD (PHASE II)

				OBS Set				Turn Set				
	Waypoint	Turn Angle (Degrees)	OBS Logic	Start Time	DTW Dist.	CDI	TO/ FROM/ OFF	Start Time	DTW Dist.	Wayline Dist.	CDI	TO/ FROM/ OFF
2.0 nmi Left	T	28	1	0841	2.5	2.2	FROM	0822	2.3	0.4	2.0	OFF
	K	111	2	1120	5.1	3.1	TO	1077	5.0	2.4	1.7	TO
	L	48	2	1438	2.6	2.5	TO	1421	2.5	0.7	1.8	TO
	M	96	2	1796	4.3	1.6	TO	1756	4.0	1.3	2.1	TO
	F	29	1	2258	3.2	2.6	FROM	2232	2.5	(26.7)*	1.7	FROM
	G	93	2	2717	3.8	2.3	TO	2686	3.9	1.0	2.0	TO
4.0 nmi Left	T	28	1	0799	4.7	4.8	OFF	0786	4.6	0.0	4.3	OFF
	K	111	2	1011	8.6	5.2	TO	0975	8.5	2.3	4.4	TO
	L	48	2	1285	4.9	4.0	TO	1256	4.7	(18.0)*	4.3	TO
	M	96	2	1594	7.4	3.3	TO	1541	7.2	1.3	4.5	TO
	F	29	1	2018	4.9	5.2	OFF	2000	4.7	(25.8)*	4.5	OFF
	G	93	2	2463	6.6	4.2	TO	2430	6.6	0.7	4.4	TO
5.0 nmi Left	T	28	1	0867	(15.0)*	6.2	TO	0827	5.9	0.1	5.6	OFF
	K	111	2	0998	10.0	5.5	TO	0985	10.5	2.6	5.3	TO
	L	48	2	1257	6.1	6.4	TO	1231	5.9	(16.1)*	5.7	TO
	M	96	2	1609	14.8	-10.2	TO	1495	7.8	(20.6)*	5.7	TO
	F	29	1	1910	5.6	5.7	OFF	1916	5.8	(25.0)*	5.9	TO
	G	93	2	2325	8.6	5.2	TO	2331	8.3	1.0	6.6	FROM

*The aircraft had passed the angle bisector and the value represented the distance TO the next wayline.

TABLE 13. OBS SET/START TURN DISTANCES FOR RIGHT OFFSETS USING THE DTW TURN METHOD (PHASE II)

				OBS Set				Turn Set				
	Waypoint	Turn Angle (Degrees)	OBS Logic	Start Time	DTW Dist.	CDI	TO/ FROM/ OFF	Start Time	DTW Dist.	Wayline Dist.	CDI	TO/ FROM/ OFF
2.0 nmi Right	T	28	2	0784	2.3	-2.3	TO	0769	2.5	0.9	-2.1	TO
	K	111	1	1233	2.6	-1.8	FROM	1189	2.4	2.4	-2.0	OFF
	L	48	1	1717	2.6	-2.3	FROM	1692	2.2	(27.2)*	-1.9	OFF
	M	96	1	2170	2.9	-2.9	FROM	2126	2.4	1.4	-2.0	OFF
	F	29	2	2677	2.3	-2.2	TO	2661	2.4	0.1	-2.0	TO
	G	93	1	3190	2.9	1.6	OFF	3184	2.7	0.8	-2.4	OFF
4.0 nmi Right	T	28	2	0848	4.4	-4.7	TO	0831	4.5	0.5	-4.4	TO
	K	111	1	1315	6.5	-5.6	TO	1293	5.9	2.2	-4.3	FROM
	L	48	1	1863	4.7	-4.3	OFF	1860	4.7	(29.8)*	-4.1	OFF
	M	96	1	2356	6.3	-4.9	TO	2349	5.9	(28.4)*	-4.2	OFF
	F	29	2	2921	4.1	-4.4	TO	2908	4.3	0.1	-4.3	TO
	G	93	1	3432	5.1	-4.0	OFF	3430	4.8	1.0	-4.0	OFF
5.0 nmi Right	T	28	2	0862	5.6	-5.8	TO	0844	5.7	1.2	-5.4	TO
	K	111	1	1360	8.4	-5.4	FROM	1352	8.1	1.6	-5.5	FROM
	L	48	1	1919	5.7	-5.8	OFF	1912	5.6	0.4	-5.4	OFF
	M	96	1	2424	7.3	-5.0	FROM	2411	6.8	(28.9)*	-4.9	FROM
	F	29	2	2979	5.4	-5.5	TO	2976	5.5	(33.5)*	-5.5	TO
	G	93	1	3502	6.9	-5.8	OFF	3496	6.7	1.3	-5.7	OFF

*The aircraft had passed the angle bisector and the value represented the distance TO the next wayline.

TABLE 14. DTW DISTANCE FOR OBS SET PRIOR TO INTERCEPTING THE FINAL APPROACH COURSE (PHASE II)

2.0 nmi left	4.0 nmi left	5.0 nmi left	2.0 nmi right	4.0 nmi right	5.0 nmi right
3.0 miles to H	1.4 miles to I	6.0 miles to H	3.0 miles to H	4.3 miles to H	6.3 miles to H

TABLE 15. RMS ($\pm$4.0 nmi) TURN DATA (PHASE II)

Technique	Turn Angle (Degrees)	Way-point	2.0 nmi left	4.0 nmi left	5.0 nmi left	2.0 nmi right	4.0 nmi right	5.0 nmi right
CDI	111	K	0.436	0.484	0.448	0.685	0.876	0.717
	48	L	0.401	0.471	0.766	0.354	0.821	0.483
	96	G	0.367	0.427	0.830	0.402	0.315	0.761
	29	F	0.149	0.173	0.900	0.521	0.173	1.058
	93	G	0.331	0.399	0.284	0.476	0.249	0.672
DTW	111	K	0.919	0.940	1.003	0.647	0.560	0.525
	48	L	0.792	0.448	0.883	0.664	0.494	0.639
	96	M	0.306	0.620	0.868	0.475	0.721	0.800
	29	F	0.327	0.333	0.341	0.208	0.141	0.129
	93	G	0.247	0.299	0.110	0.315	0.381	0.154

STEADY STATE DATA -- TOTAL SYSTEM CROSSTRACK ERROR AND FLIGHT TECHNICAL ERROR. Table 16 presents the mean and RMS statistics for the offset steady state TSCT data for all segments between waypoints C' and H (or H'). The statistics were computed based on the time-series data from 4 nmi after the waypoint to 4 nmi prior to the waypoint. This range caused steady state data not to exist for the 4-nmi left offset between waypoints G and H and for the 5-nmi left offset between waypoints T and K, and between waypoints G and H. The data between these points were included in the turn data statistics.

The data in these tables can be combined for both the CDI and DTW conditions since: (1) the tracking data should not be influenced, over the long run, by the turn anticipation method, and (2) the ±4-nmi window used for the turn data should delete all transition data from the steady state data.

Table 16 shows that the 5-nmi left and right offsets resulted in TSCT values that either approach or exceeded the 2-RMS criteria of ±2 nmi. The 2- and 4-nmi offset TSCT error data in all cases was less than the ±2 nmi criteria.

Table 17 presents the mean and RMS statistics for the offset steady state CDI displacement (FTE) data for all segments between waypoints C' and H. The statistics were computed on the same basis as the TSCT data. Table 17 indicates that a bias did indeed exist for the 5-nmi left offset (i.e., right CDI needle displacement) which in turn influenced the TSCT data especially for the segments between waypoints K to L and waypoints L to M.

In general, these data indicate that the tracking proficiency for the 5-nmi offsets did not fall within the criteria established by AC 90-45A. Analog single-waypoint RNAV systems of the type used in this study which utilize a noncentered needle for offsets would probably violate the airspace utilization criteria in the terminal area and not be useable for offsets greater than 4 nmi.

PHASE III METHOD OF APPROACH (2- AND 4-NMI OFFSET PROCEDURES)

OBJECTIVE.

The objective of phase III was to expand the offset tracking data base which was established during phase II, and to evaluate the use of a noncentered CDI needle to fly 2- and 4-nmi offsets in a terminal area environment.

The phase II tests demonstrated that the pilots could use a procedural turn anticipation method based on an OBS set logic and CDI distance (and/or rate of movement) to anticipate turns while maintaining the desired offset using a noncentered needle CDI. The phase II study also pointed out that the procedure did not work for the transition to the final approach course, and that a procedure (or logic) would have to be derived which would allow the pilots to successfully transition from the offset course to the final course.

The rationale for the CDI-based turn anticipation technique was presented in the corresponding section of phase II.

TABLE 16. MEAN AND RMS STEADY STATE TRACKING DATA (TSCT) (PHASE II)

TECHNIQUE	SEGMENT	2.0 nmi left $\overline{X}$	2.0 nmi left RMS	4.0 nmi left $\overline{X}$	4.0 nmi left RMS	5.0 nmi left $\overline{X}$	5.0 nmi left RMS	2.0 nmi right $\overline{X}$	2.0 nmi right RMS	4.0 nmi right $\overline{X}$	4.0 nmi right RMS	5.0 nmi right $\overline{X}$	5.0 nmi right RMS
CDI	C'-T	0.591	0.601	0.266	0.512	0.400	0.509	0.077	0.185	-0.398	0.626	-0.937	1.048
	T-K	0.534	0.542	0.475	0.475			-0.023	0.211	0.411	0.460	-0.237	0.286
	K-L	-0.261	0.454	-0.383	0.444	-1.032	1.033	-0.594	0.632	-0.557	0.670	-0.935	0.985
	L-M	-0.446	0.457	-0.746	0.771	-1.023	1.043	-0.959	1.019	-0.432	0.675	-1.326	1.385
	M-F	-0.182	0.317	-0.380	0.534	-0.230	0.373	-0.498	0.533	-0.230	0.267	-0.651	0.770
	F-G	0.011	0.187	-0.388	0.423	-0.866	0.887	-0.375	0.416	-0.405	0.447	-0.823	0.893
	G-H	0.398	0.399					-0.217	0.223	0.103	0.213	-0.693	0.732
DTW	C'-T	0.587	0.605	0.198	0.340	0.235	0.584	0.222	0.331	-0.115	0.256	-0.087	0.280
	T-K	0.817	0.818	0.769	0.770			0.260	0.288	-0.154	0.159	-0.273	0.282
	K-L	-0.317	0.331	-0.917	0.926	-1.258	1.261	-0.902	0.904	-0.732	0.752	-0.933	0.940
	L-M	-0.759	0.794	-0.689	0.703	-1.025	1.051	-0.793	0.798	-0.846	0.879	-0.857	0.870
	M-F	-0.070	0.138	0.053	0.190	0.434	0.958	-0.234	0.293	-0.183	0.243	-0.073	0.219
	F-G	0.053	0.170	0.205	0.282	-0.273	0.296	-0.066	0.130	-0.369	0.434	-0.068	0.176
	G-H	0.318	0.318					-0.025	0.224	-0.020	0.230	-0.299	0.568

TABLE 17. MEAN AND RMS STEADY STATE CDI DISPLACEMENT (FTE) (PHASE II)

Technique	Segment	2.0 nmi left		4.0 nmi left		5.0 nmi left		2.0 nmi right		4.0 nmi right		5.0 nmi right	
		$\overline{X}$	RMS	$\overline{X}$	RMS	$\overline{X}$	RMS	$\overline{X}$	RMS	$\overline{X}$	RMS	$\overline{X}$	RMS
CDI	C'-T	1.761	1.817	4.412	4.428	5.372	5.378	-2.035	2.053	-3.615	3.887	-4.461	4.497
	T-K	1.794	1.798	4.419	4.420			-2.164	2.171	-3.416	3.978	-4.069	4.675
	K-L	1.753	1.801	4.225	4.231	5.913	5.914	-2.076	2.087	-4.173	4.291	-5.094	5.106
	L-M	2.160	2.165	4.507	4.513	5.856	5.862	-1.799	1.861	-4.354	4.388	-4.656	4.688
	M-F	2.012	2.098	4.017	4.644	4.920	5.379	-1.498	1.537	-3.876	4.225	-4.724	4.772
	F-G	1.916	1.924	4.573	4.575	6.112	6.119	-1.925	1.936	-4.158	4.224	-4.758	4.805
	G-H	1.545	1.546					-2.098	2.100	-4.074	4.086	-4.584	4.768
DTW	C'-T	2.066	2.095	4.293	4.305	5.455	5.482	-1.938	1.992	-4.168	4.186	-5.209	5.223
	T-K	1.740	1.743	4.033	4.034			-2.129	2.131	-4.391	4.391	-5.389	5.391
	K-L	1.839	1.857	4.525	4.526	6.022	6.023	-1.970	1.974	-4.327	4.338	-5.235	5.275
	L-M	2.258	2.349	4.480	4.483	5.892	5.898	-1.928	1.933	-4.246	4.254	-5.324	5.327
	M-F	2.124	2.143	4.196	4.203	4.950	5.067	-2.087	2.098	-4.234	4.347	-5.468	5.473
	F-G	2.059	2.066	4.120	4.127	5.518	5.519	-2.126	2.139	-4.176	4.268	-5.354	5.393
	G-H	1.821	1.821					-2.072	2.090	-3.933	4.299	-3.789	4.932

ROUTE STRUCTURE.

All RNAV flights were flown using the route B1 configuration presented in figure 7 and 13. Figure 13 shows the 2- and 4-nmi left and right offset configurations. The phase III study was conducted using only the 2- and 4-nmi left and right offsets. The phase II tests showed that 5-nmi offsets were not practical due to equipment limitations.

EXPERIMENTAL DESIGN.

The experimental design used for phase III was specifically devised to test whether or not significant differences in horizontal tracking performance existed between the four offset configurations (2- left, 4-nmi left, 2- right, and 4-nmi right) for steady state tracking; and to determine if the angle or direction affected tracking performance.

The experimental design matrix for this study is presented in table 18. It can be seen that a familiarization flight preceded the data collection flights, and that half of the subjects were tested on the left offsets first, while the remainder were tested on the right offsets first. In addition, the order of presentation of the offsets was counter-balanced so that the 2- and 4-nmi offsets were presented first an equal number of times.

TABLE 18. EXPERIMENTAL DESIGN CONFIGURATIONS (PHASE III)

		Data Flights			Data Flights	
Subject No.	FAM*	4 nmi left	2 nmi left	FAM	2 nmi right	4 nmi right
1	1	2	3	4	5	6
2	1	3	2	4	6	5
3	4	5	6	1	2	3
4	4	6	5	1	3	2
5	1	2	3	4	5	6
6	1	3	2	4	6	5
7	4	5	6	1	2	3
8	4	6	5	1	3	2

* Familiarization Flight

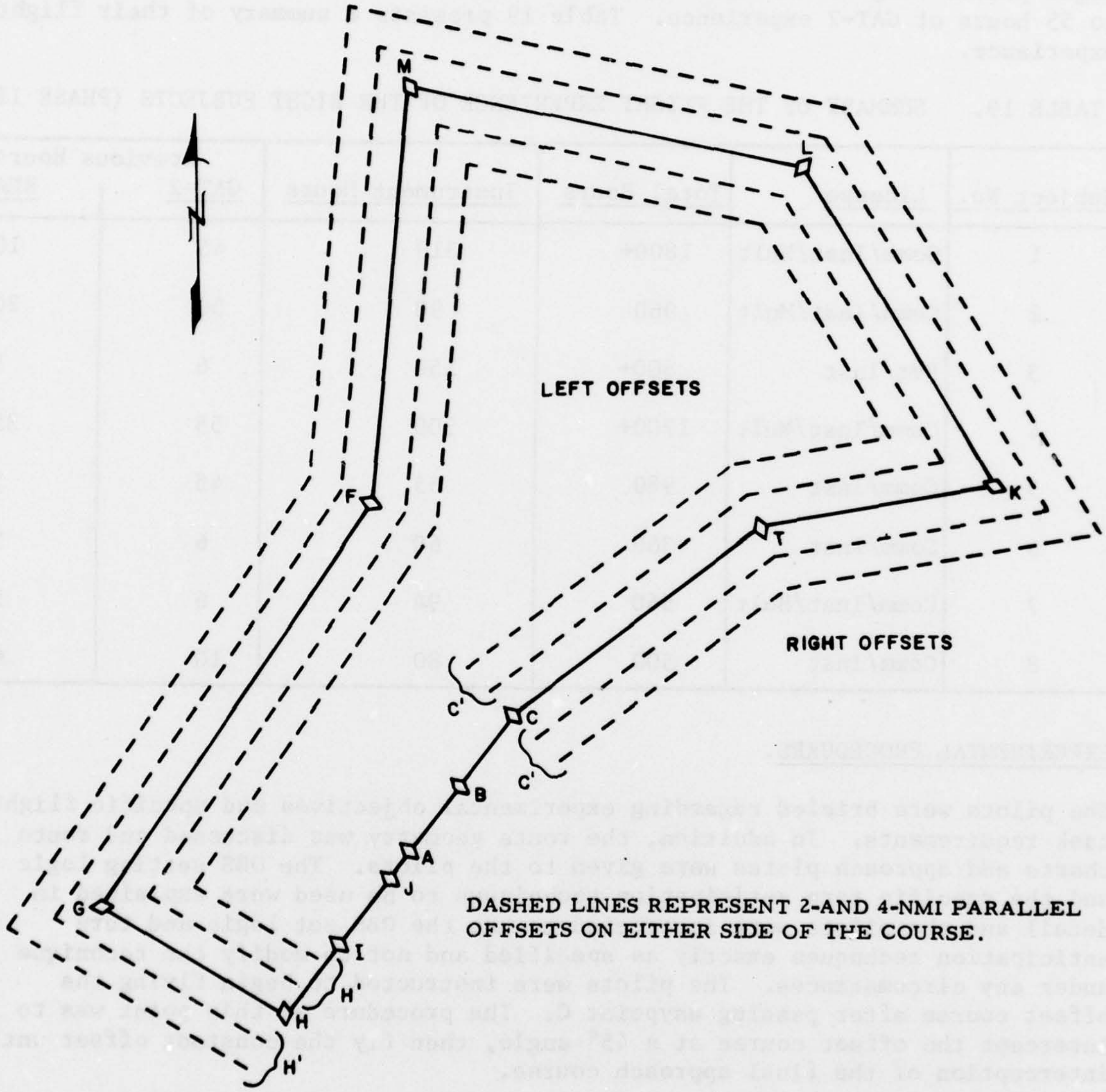


FIGURE 13. HORIZONTAL VIEW OF THE EXPERIMENTAL FLIGHT COURSE (PHASE III)

SUBJECTS.

The eight subject pilots in this experiment were chosen from instrument rated pilots (at NAFEC) who had participated in previous GAT-2A RNAV projects. The eight pilots ranged in flight experience from 350 to 1,800 total hours and 6 to 55 hours of GAT-2 experience. Table 19 presents a summary of their flight experience.

TABLE 19. SUMMARY OF THE FLIGHT EXPERIENCE OF THE EIGHT SUBJECTS (PHASE III)

Subject No.	License	Total Hours	Instrument Hours	Previous Hours GAT-2	Previous Hours RNAV
1	Comm/Inst/Mult	1800+	310	45	10
2	Comm/Inst/Mult	960	90	50	20
3	Pvt/Inst	800+	150	6	5
4	Comm/Inst/Mult	1700+	300	55	35
5	Comm/Inst	980	65	45	5
6	Comm/Inst	360	60	6	5
7	Comm/Inst/Mult	560	94	6	5
8	Comm/Inst	500	80	10	6

EXPERIMENTAL PROCEDURES.

The pilots were briefed regarding experimental objectives and specific flight task requirements. In addition, the route geometry was discussed and route charts and approach plates were given to the pilots. The OBS setting logic and the specific turn anticipation techniques to be used were explained in detail and the pilots were instructed to use the OBS set logic and turn anticipation technques exactly as specified and not to modify the technique under any circumstances. The pilots were instructed to begin flying the offset course after passing waypoint C. The procedure at this point was to intercept the offset course at a 45° angle, then fly the constant offset until interception of the final approach course.

During the offset flight, the pilot was expected to maintain an altitude of 12,000 feet and 160 knots indicated airspeed (i.e., approximately 195 knots TAS). The pilot was instructed to begin his descent to 2,000 feet at a point approximately 5 nmi after waypoint F.

The charts defined the OBS, theta, rho, and frequency for each waypoint. After the pilots set the OBS, theta, rho, and frequency for a given waypoint, they were flying TO that waypoint. The TO flag was displayed on the CDI and DTW was decreasing. When they reached the wayline, the TO flag (within approximately +0.5 nmi) disappeared and the DTW stopped decreasing (DTW did not reach zero, but approximated the offset distance).

The pilots were instructed to make an extra effort to fly with the CDI needle at the selected offset distance at all times. Furthermore, when starting the flight, the pilots were instructed to make sure that the RNAV Mode Selector switch was in RNAV Mode. The only time the pilots were allowed to use the Approach Mode was on final approach. Each pilot was given two familiarization flights before starting actual data collection (table 18). Specific charts were provided for the familiarization flights. The pilots were instructed that they could expect to encounter some mild turbulence with winds aloft during the flight. The simulator operator advised the pilots of these winds and other weather phenomena while also issuing air traffic control (ATC) clearances. Upon completion of the familiarization flight, the subject pilot was immediately tested on the appropriate offset flights (reference table 18).

SPECIFIC TECHNIQUE FOR OFFSET TRACKING USING A CDI-BASED TURN ANTICIPATION TECHNIQUE. The technique used in this phase III effort consisted of three distinct required actions:

1. Implementation of the OBS set logic

2. Implementation of the turn logic

3. Implementation of the final approach intercept logic

LOGIC FOR SETTING OBS DURING OFFSET TRACKING.

Course Change	Logic
(1) Right offset/turn right	Twice offset value
(2) Right offset/turn left	TO/FROM indicator
(3) Left offset/turn left	Twice offset value
(4) Left offset/turn right	TO/FROM indicator

In general, the rules for setting the OBS (for the next course) during offset tracking are as follows:

1. When on an offset and the next course turn occurs after passing the waypoint, use the TO/FROM indicator as a cue for setting the OBS to the next course (reference cases b and d above). It should be noted that when crossing the wayline (a line perpendicular to the course through the

waypoint) the TO/FROM flag is neither TO nor FROM but is "buried out of view." At this point, set the OBS for the next course.

2. When on an offset and the next course turn occurs prior to the waypoint, use a value that is twice the offset distance for setting the OBS to the next course. For example, if a 4.0-nmi offset is being flown, the OBS will be set when DTW reads 8.0 nmi (reference cases a and c above). Figure 12 represents the placard which was mounted directly above the RNAV unit. This placard was to be used by the pilot to assist in applying rules 1 and 2.

TURN LOGIC. Once the OBS has been set, the CDI needle will move from its present position and will either be pegged (at the extremes of the display) or will move toward the center of the display. The pilot will continue to maintain his present heading until the CDI needle approaches the desired offset distance. As the CDI needle approaches the desired offset distance, the pilot will have to use his judgment (based on the rate of CDI movement) to initiate his turn to the next course. As the aircraft is turning to the next course, the pilot will monitor the CDI needle until it reaches the desired offset distance. Pilots are expected to turn at a rate not to exceed 3° per second which is the standard rate turn. The pilot should bear in mind that the faster the airspeed, the faster the CDI needle movement, and the more he will have to lead his turn.

TURN LOGIC FOR FINAL APPROACH TECHNIQUE.

1. Left offset (or right offset) inside base leg (i.e., offset track is between the final approach fix and the initial approach fix for the final approach course).

Rules:

a. After completing turn at GOLF, update to INDIA waypoint.
b. After updating waypoint, set OBS to 038° final approach course.
c. Maintain current heading to intercept final approach course.
d. Use CDI as guide for turning onto final approach course.

2. Right offset (or left) outside base leg (i.e., offset track is beyond the initial approach fix).

Rules:

a. After completing turn at GOLF, update to HOTEL waypoint.
b. After updating waypoint (track offset CDI needle) until twice the offset distance (DTW) to set OBS to the next course.
c. Use CDI as guide for turning onto final approach course.

These rules for the OBS setting logic were derived by experimentation and actual testing, and appeared to offer a reliable means of establishing when the OBS should be set.

DATA COLLECTION PARAMETERS.

The data items extracted included:

a. TSCT turn data related to the transition from one segment to the next. These data were defined by envelopes (±2 and/or ±4 nmi) before and after a waypoint. These envelopes were sufficiently large to encompass all activities related to transitioning from one segment to the next.

b. Steady state TSCT and FTE data.

c. Actual start turn distance (DTW, DWYLIN, and time) used by the pilot. The heading time history data was used to establish this point.

d. Actual turn end distance (DTW, DWYLIN, and time) used by the pilot. The heading time history data was used to establish this point.

e. OBS setting (DTW, DWYLIN, and time).

DISCUSSION OF DATA.

DATA REDUCTION -- OBS SET/START TURN DATA. The first level of data reduction was directed toward extracting operational data concerning the ability of the pilots to perform their RNAV-related navigation tasks in order to comply with the assigned turn anticipation procedures.

Table 20 contains the OBS setting and start turn values for the following parameters: (1) DTW distance, (2) Wayline distance, and (3) CDI displacement. The statistical values in this table are means. These values are presented as a function of turn angle (i.e., waypoint location and transition angle) and offset configuration, and are a summary of the operational data from all eight subjects.

The data show that, for the most part, the pilots did apply the rules established for the OBS setting logic. For the left offsets, four of the six turns required that the OBS be set at a distance that was two times the offset value. From these data, it appears that the pilots did not have a problem with using the required rule. The other two turns (at waypoints T and F) required that the OBS be set upon movement of the TO/FROM indicator. From these data, it can be seen that the required action resulted in the OBS being set at a DTW distance equivalent to the offset distance, which, in turn, required the pilots to initiate the transition to the next segment almost immediately.

From table 20, it is evident that for the right offsets, four of the six turns required that the OBS be set upon movement of the TO/FROM indicator. It appears that the pilots did not have a problem with using the required rule. The other two turns (at waypoints T and F) required that the OBS be set at a distance that was two times the offset value. The data indicate that the required action was implemented at the desired DTW distance.

TABLE 20. OBS SET/START TURN DISTANCE FOR 2- AND 4-MILE LEFT AND RIGHT OFFSETS (PHASE III)

				DTW Distance		Wayline Distance		CDI Displacement	
	Waypoint	Turn Angle (Degrees)	*OBS Logic	OBS Set	Start Turn	OBS Set	Start Turn	OBS Set	Start Turn
2.0 nmi Left Offset	T	28	1	2.59	2.71	1.03	6.26	1.99	2.26
	K	111	2	4.15	3.84	1.11	0.75	2.71	2.38
	L	48	2	4.51	2.85	2.83	0.80	4.23	2.61
	M	96	2	4.30	8.05	1.43	3.40	3.35	2.44
	F	29	1	2.45	2.56	7.09	17.20	2.13	2.38
	G	93	2	4.83	3.64	1.95	1.74	4.18	2.66
	H	84	3	7.21	4.56	5.88	0.99	5.85	0.99
4.0 nmi Left Offset	T	28	1	4.35	4.44	2.24	3.86	4.04	4.10
	K	111	2	7.79	7.18	3.36	2.65	5.11	4.76
	L	48	2	8.54	5.81	4.98	3.24	8.66	5.63
	M	96	2	8.45	6.74	2.64	6.13	7.04	4.70
	F	29	1	4.48	4.59	0.79	10.21	4.20	4.40
	G	93	2	8.28	7.29	3.19	1.90	6.80	5.53
	H	84	3	5.51	2.60	4.46	1.23	4.78	0.91
2.0 nmi Right Offset	T	28	2	3.95	2.68	2.31	4.49	-3.43	-2.41
	K	111	1	2.45	3.03	2.76	1.54	0.18	-0.93
	L	48	1	2.33	2.96	0.60	20.26	-1.78	-2.64
	M	96	1	2.45	2.71	2.00	1.18	-0.44	-1.15
	F	29	2	4.24	2.81	2.63	12.26	-3.49	-2.50
	G	93	1	3.98	2.69	1.96	2.59	-0.11	-4.66
	H	84	3	4.23	2.41	3.00	0.99	3.20	0.88
4.0 nmi Right Offset	T	28	2	7.80	5.39	5.06	4.74	-7.08	-4.84
	K	111	1	4.60	6.29	5.90	2.04	1.01	-2.81
	L	48	1	4.46	5.38	4.93	7.49	-3.51	-4.69
	M	96	1	4.34	5.43	4.31	4.90	-0.30	-3.01
	F	29	2	7.34	4.85	8.26	16.70	-6.54	-4.59
	G	93	1	4.40	5.30	4.08	1.43	-0.11	-2.78
	H	84	3	8.58	5.63	6.53	1.46	7.00	1.38

* 1 - Used To/From Logic
2 - Used Two Times Offset Distance
3 - Used Final Approach Logic

The turn at waypoint H was not considered in the above explanations since the logic for the transition to the final approach course was different than the other two turn logics. The data in table 20, however, indicate that the pilots followed the required logic.

Even though the pilots adhered to the OBS setting logic for both the left and right offsets, the turn logic appears to have caused considerable variability in times and distances for the right offsets. The left offset CDI displacement values are consistent with that which was expected. Also, the pilots did perform as expected and initiated the transition to the next course at the appropriate point. An explanation concerning the expected CDI needle movement was included in the phase II section of this report.

TOTAL SYSTEM CROSSTRACK ERROR -- TURN DATA. The second level of data reduction was directed toward measurement of crosstrack error during the transitions at waypoints T, K, L, M, F, and G in order to determine if the turn logic resulted in turns which exceeded a 2-RMS value of ±1.5 nmi. Table 21 presents the mean, sigma, and RMS statistics based on the time-series data from 2 nmi prior to the waypoint to 2 nmi after the waypoint. Table 22 presents the mean, sigma, and RMS statistics based on the time-series data from 4 nmi prior to the waypoint to 4 nmi after the waypoint. It is evident that the RMS variability was greater for the left offsets than for the right offsets, and that the 4-nmi left offset transition at waypoint L exceeded a 2-RMS value of ±1.5 nmi. The difference in variability between the left and right offsets may be attributable to the right CDI needle bias (table 10). The total system crosstrack error for the turn data at waypoint H was consistent with the turn data at the other waypoints and did not exceed a 2-RMS value of ±1.5 nmi. None exceeded a 2-RMS value of ±2 nmi.

STEADY STATE DATA -- TOTAL SYSTEM CROSSTRACK ERROR AND FLIGHT TECHNICAL ERROR. Table 23 presents the mean, sigma, and RMS statistics for the offset steady state tracking data (i.e., TSCT) for all segments between waypoints C' and H (or H'). The same statistics were also computed for all tracking data between waypoint H (or H') and waypoint J; however, these data were based upon using the RNAV approach mode (i.e., 1 dot=1/4 mile). The statistics were computed based on the time-series data from 2 nmi after the waypoint to 2 nmi prior to the waypoint. An evaluation of the turn and steady state tracking data indicated that the ±2-nmi turn data window was sufficient to encompass all of the turn data and that the steady state data was not affected by the turn data.

The data show that in three segments tracking performance resulted that exceeded a 2-RMS value of ±1.5 nmi. Two of these occurred during the 4-nmi left offset, and the third occurred during the 2-nmi left offset. Only one of these three exceeded a 2-RMS value of ±2 nmi.

In general, the left offsets were more variable (in terms of TSCT error) than the right offsets. Once again, this may have been due to the CDI needle bias.

TABLE 21. TURN DATA -- TSCT ERROR (±2.0-NMI WINDOW) (PHASE III)

	2-nmi Left Offset			4-nmi Left Offset			2-nmi Right Offset			4-nmi Right Offset			Summary			
Segment	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	2 RMS
T 28°	0.451	0.185	0.550	0.512	0.190	0.586	0.306	0.159	0.388	0.539	0.223	0.631	0.452	0.189	0.539	1.077
K 111°	0.299	0.282	0.448	0.395	0.427	0.619	-0.223	0.402	0.552	-0.385	0.363	0.609	0.021	0.368	0.557	1.114
L 48°	-0.331	0.172	0.497	-0.959	0.234	0.992	-0.196	0.282	0.458	-0.307	0.178	0.425	-0.449	0.217	0.593	1.186
M 96°	0.232	0.351	0.437	0.039	0.388	0.463	-0.191	0.230	0.322	-0.460	0.211	0.521	-0.095	0.296	0.435	0.870
F 29°	-0.350	0.201	0.441	-0.158	0.070	0.212	-0.272	0.107	0.322	-0.269	0.160	0.365	-0.262	0.135	0.335	0.670
G 93°	0.390	0.285	0.527	-0.087	0.328	0.675	0.159	0.227	0.338	-0.159	0.199	0.318	0.076	0.260	0.464	0.928
Average RMS			0.483			0.591			0.396			0.478				
H 84°	0.277	0.407	0.504	-0.130	0.364	0.652	-0.086	0.250	0.418	0.169	0.299	0.474	-0.027	0.330	0.512	1.024

TABLE 22. TURN DATA -- TSCT ERROR (±4.0-NMI WINDOW)

	2-nmi Left Offset			4-nmi Left Offset			2-nmi Right Offset			4-nmi Right Offset			Summary			
Segment	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	2 RMS
T 28°	0.516	0.203	0.589	0.594	0.258	0.664	0.349	0.168	0.416	0.404	0.296	0.550	0.466	0.231	0.555	1.110
K 111°	0.242	0.405	0.507	0.299	0.536	0.636	0.183	0.435	0.531	-0.282	0.459	0.583	0.019	0.459	0.564	1.128
L 48°	-0.326	0.215	0.489	-0.899	0.246	0.935	-0.285	0.305	0.515	-0.361	0.214	0.459	-0.468	0.245	0.600	1.200
M 96°	0.087	0.363	0.412	0.003	0.513	0.583	-0.276	0.250	0.381	-0.474	0.204	0.529	-0.165	0.332	0.476	0.952
F 29°	-0.333	0.231	0.453	-0.129	0.123	0.248	-0.290	0.114	0.328	-0.348	0.219	0.446	-0.275	0.172	0.369	0.738
G 93°	0.435	0.270	0.570	0.041	0.364	0.660	0.177	0.215	0.339	-0.068	0.213	0.320	0.146	0.266	0.472	0.944
Average RMS			0.503			0.621			0.418			0.481				
H 84°	0.369	0.418	0.564	0.068	0.390	0.536	0.012	0.263	0.350	0.053	0.303	0.413	0.093	0.343	0.466	0.932

TABLE 23. MEAN, SIGMA, AND RMS STEADY STATE TRACKING DATA (TSCT) (PHASE III)

Segment	2-nmi Left Offset			4-nmi Left Offset			2-nmi Right Offset			4-nmi Right Offset			Summary	
	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	RMS	2 RMS
C* - T	0.543	0.385	0.711	0.883	0.583	1.062	0.244	0.361	0.451	-0.084	0.535	0.607	0.707	1.414
T - K	0.605	0.169	0.646	0.739	0.196	0.784	0.317	0.182	0.395	0.284	0.209	0.361	0.546	1.092
K - L	-0.328	0.163	0.398	-0.606	0.193	0.639	-0.582	0.222	0.628	-0.509	0.219	0.567	0.558	1.116
L - M	-0.334	0.222	0.420	-0.529	0.238	0.594	-0.486	0.295	0.588	-0.519	0.307	0.668	0.567	1.134
M - F	-0.072	0.233	0.309	-0.059	0.341	0.466	-0.361	0.203	0.427	-0.338	0.234	0.442	0.411	0.822
F - G	-0.067	0.312	0.409	-0.037	0.297	0.398	-0.119	0.220	0.311	-0.275	0.271	0.438	0.389	0.778
G - H	0.774	0.162	0.835	0.471	0.159	0.587	0.121	0.197	0.287	0.025	0.143	0.366	0.518	1.036
Average RMS			.533			.647			.441			.493		
H - J	0.136	0.081	0.174	0.043	0.076	0.160	0.189	0.124	0.232	0.152	0.095	0.183	0.187	0.374

*The data for these segments was based on using the RNAV Approach Mode (1 dot = 1/4 mile) and was center needle tracking.

These data indicate that the tracking proficiency (TSCT error), except for three offset cases, do fall within either a 2-RMS value of ± 1.5 nmi or a 2-RMS value of ± 2 nmi for the steady state data. These data, however, are influenced by one pilot's initial flights which were the 2-nmi and 4-nmi left offsets. This pilot was a minimum-time IFR pilot (approximately 60 hours) and he had the lowest overall time (approximately 360 hours). This particular subject improved his performance over subsequent flights, and by his last flight (i.e., sixth - including two familiarization flights) it was difficult to distinguish his performance from the other seven pilots.

Figure 14 presents RMS TSCT error for the steady state data and the turn data (both ± 2- and ± 4-nmi error window). The difference in variability between the left and right offsets exists for both the steady state and the turn data; furthermore, it is evident that there is no difference in the magnitude of the steady state and turn data. This similarity in both data sets would suggest that the turn logic works and does not result in errors larger than those incurred for the steady state tracking.

Figures 15 through 18 present the composite plots for the 2-nmi left, 4-nmi left, 2-nmi right, and 4-nmi right offsets.

Table 24 presents the mean, sigma, and RMS statistics for the offset steady state CDI displacement (FTE) for all segments between waypoints C' and H (or H'). The same statistics were also computed for all tracking data between waypoint H (or H') and waypoint J; however, these data were based upon using the RNAV approach mode (i.e., 1 dot = 1/4 mile). The statistics were computed on the same basis as the TSCT data. It can be seen that for the steady state tracking data there was no difference between the left and right offsets in terms of CDI displacement. The bias apparent in the calibration measurements (table 23), does not appear to have affected the pilots' tracking capability for the steady state segments.

The steady state TSCT error for the final approach course was based on the centerline course (i.e., deviations were for a centered CDI needle), and, as such, was more precise than that for the offset tracking.

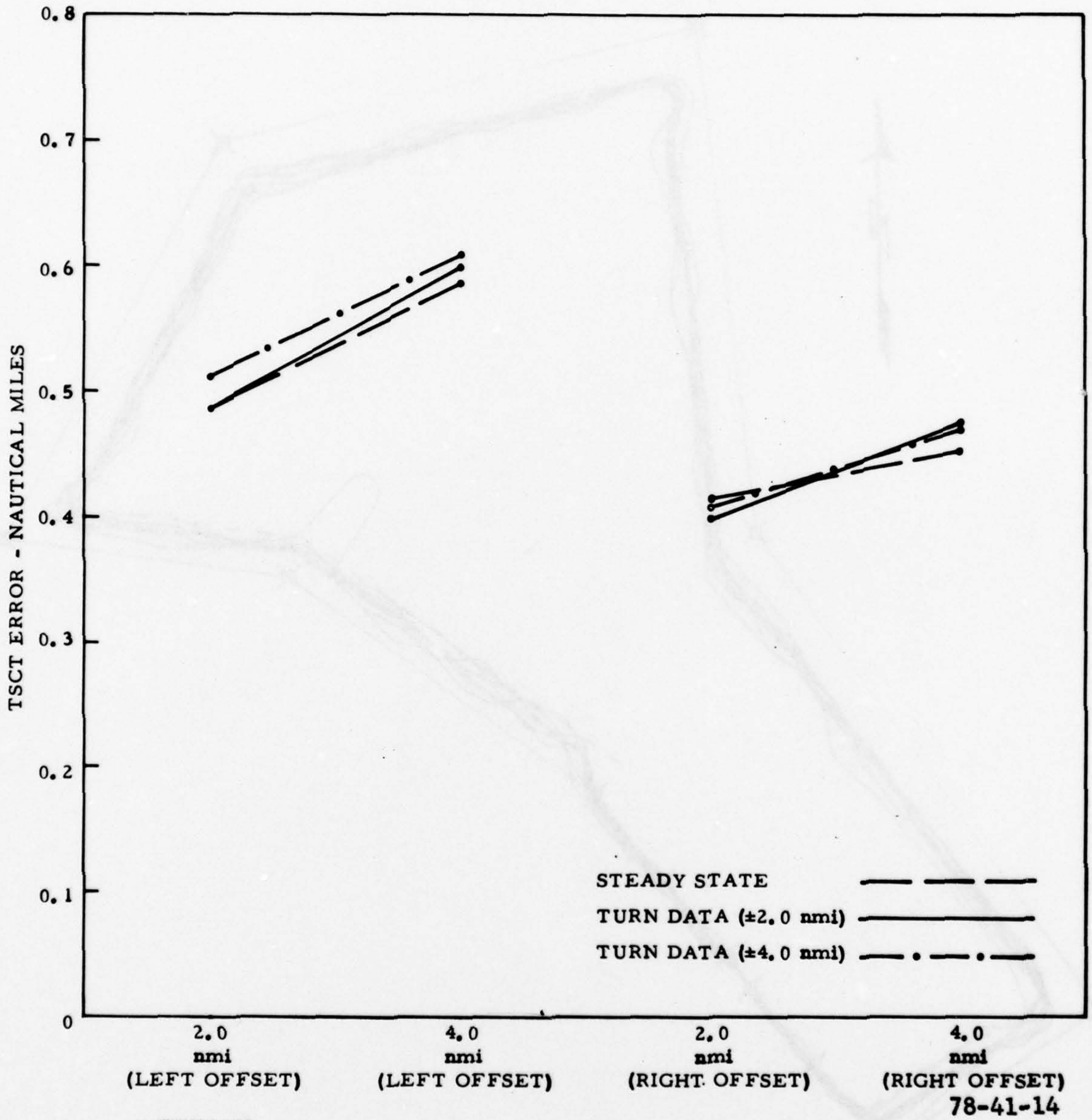


FIGURE 14. RMS TSCT ERROR--TURN DATA (±2-AND 4-NMI ERROR WINDOW) AND STEADY STATE DATA (PHASE III)

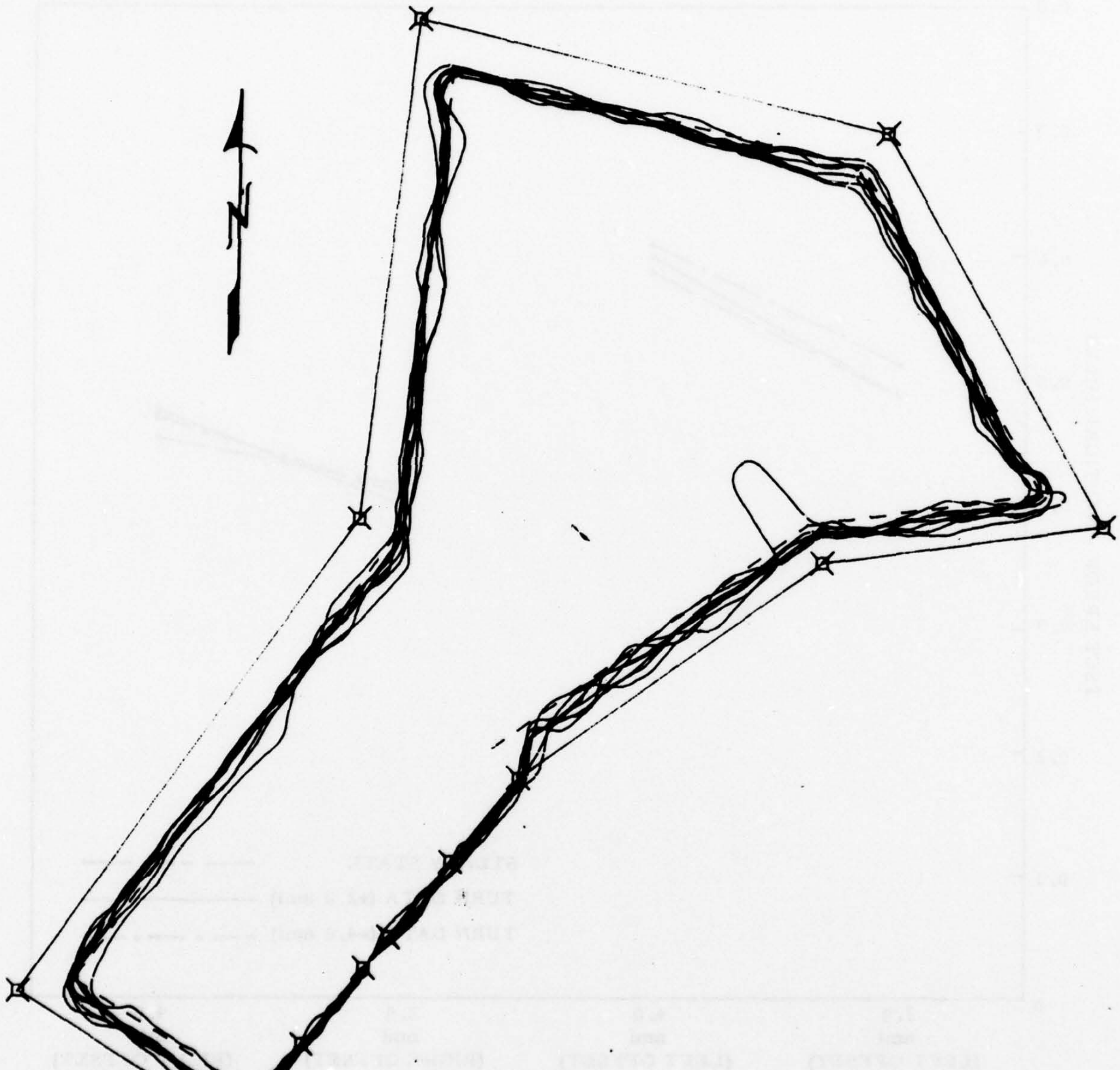


FIGURE 15. COMPOSITE PLOT FOR 2-NMI LEFT OFFSET (PHASE III)

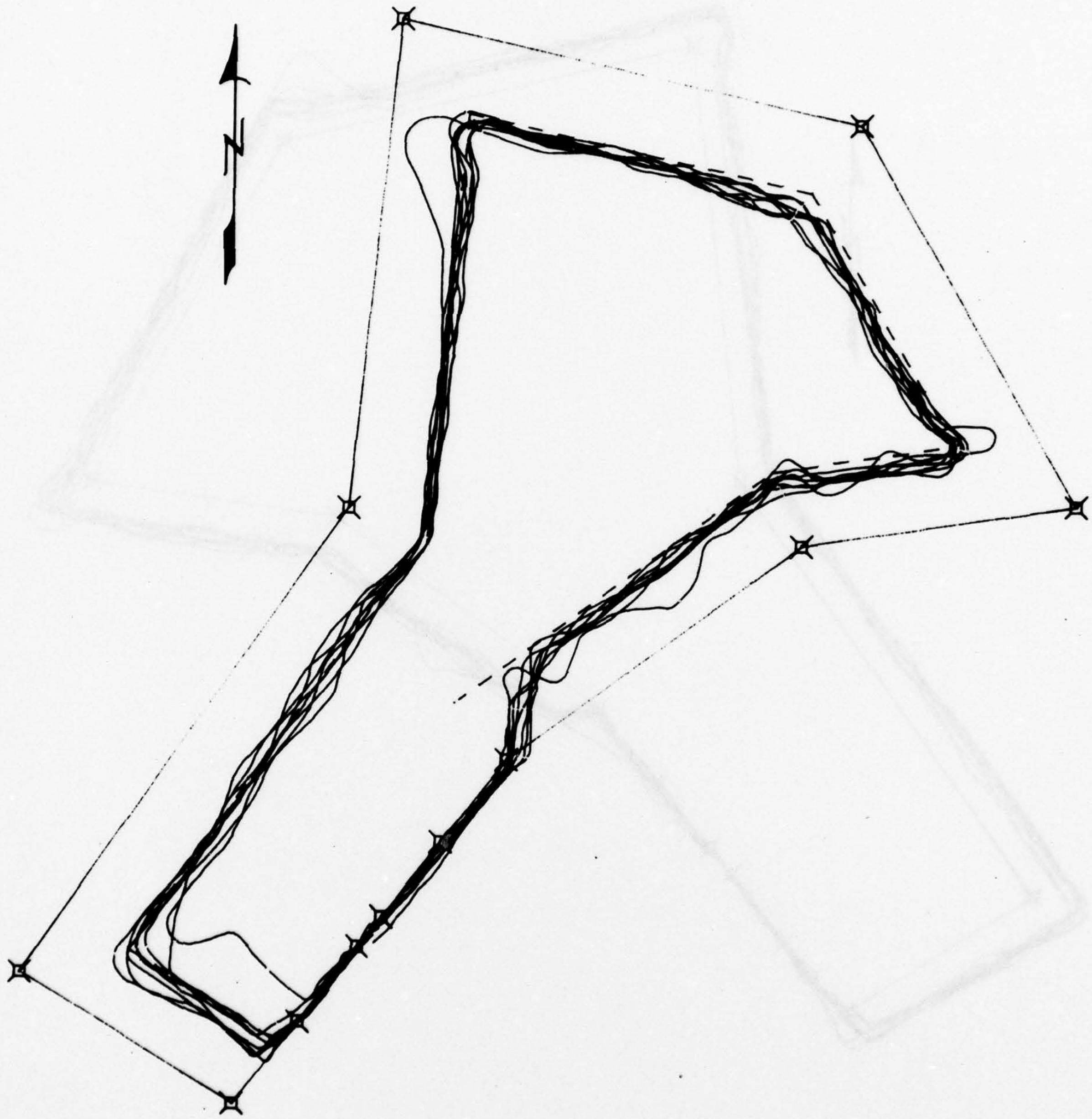


FIGURE 16. COMPOSITE PLOT FOR 4-NMI LEFT OFFSET (PHASE III)

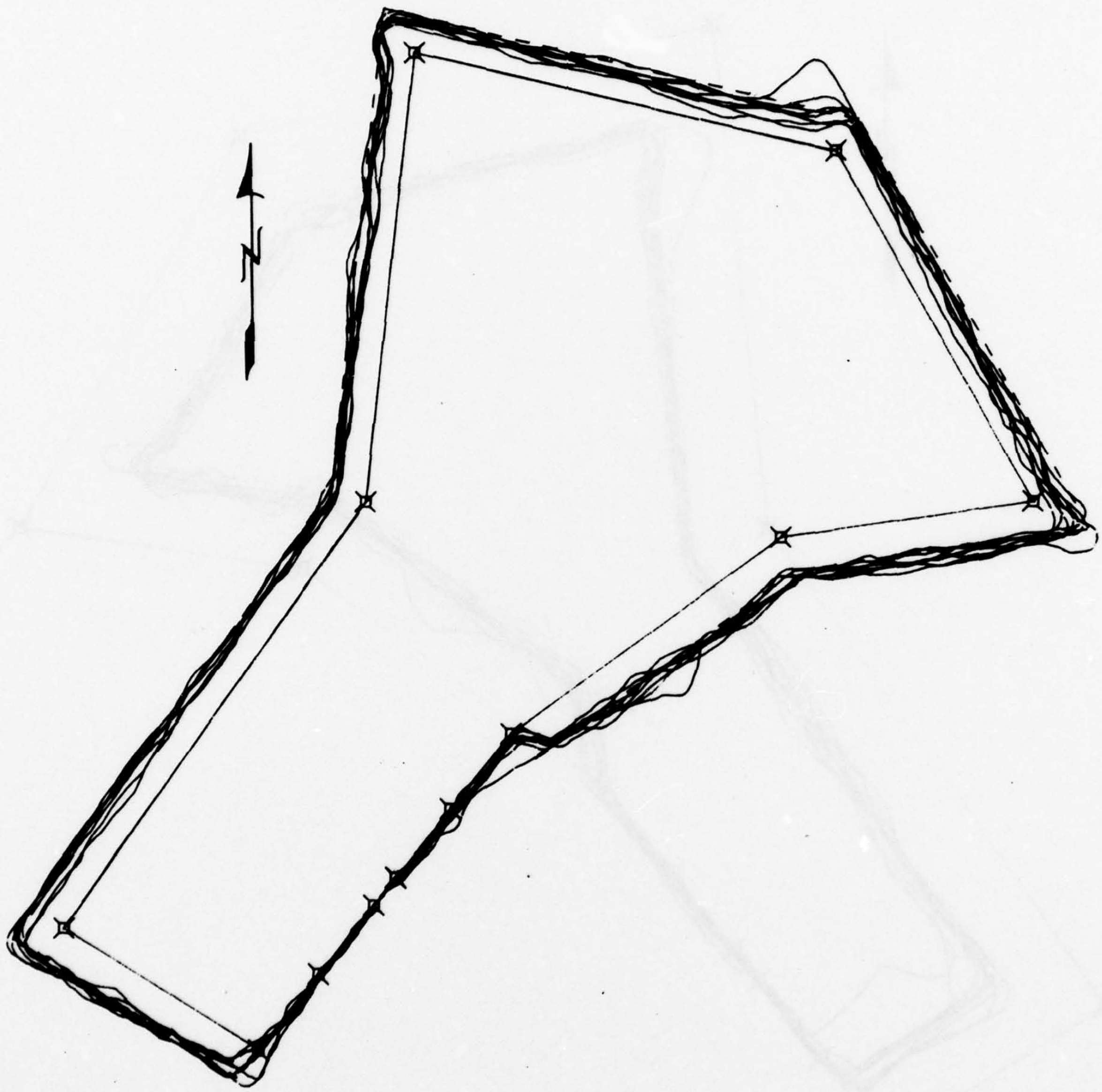


FIGURE 17. COMPOSITE PLOT FOR 2-NMI RIGHT OFFSET (PHASE III)

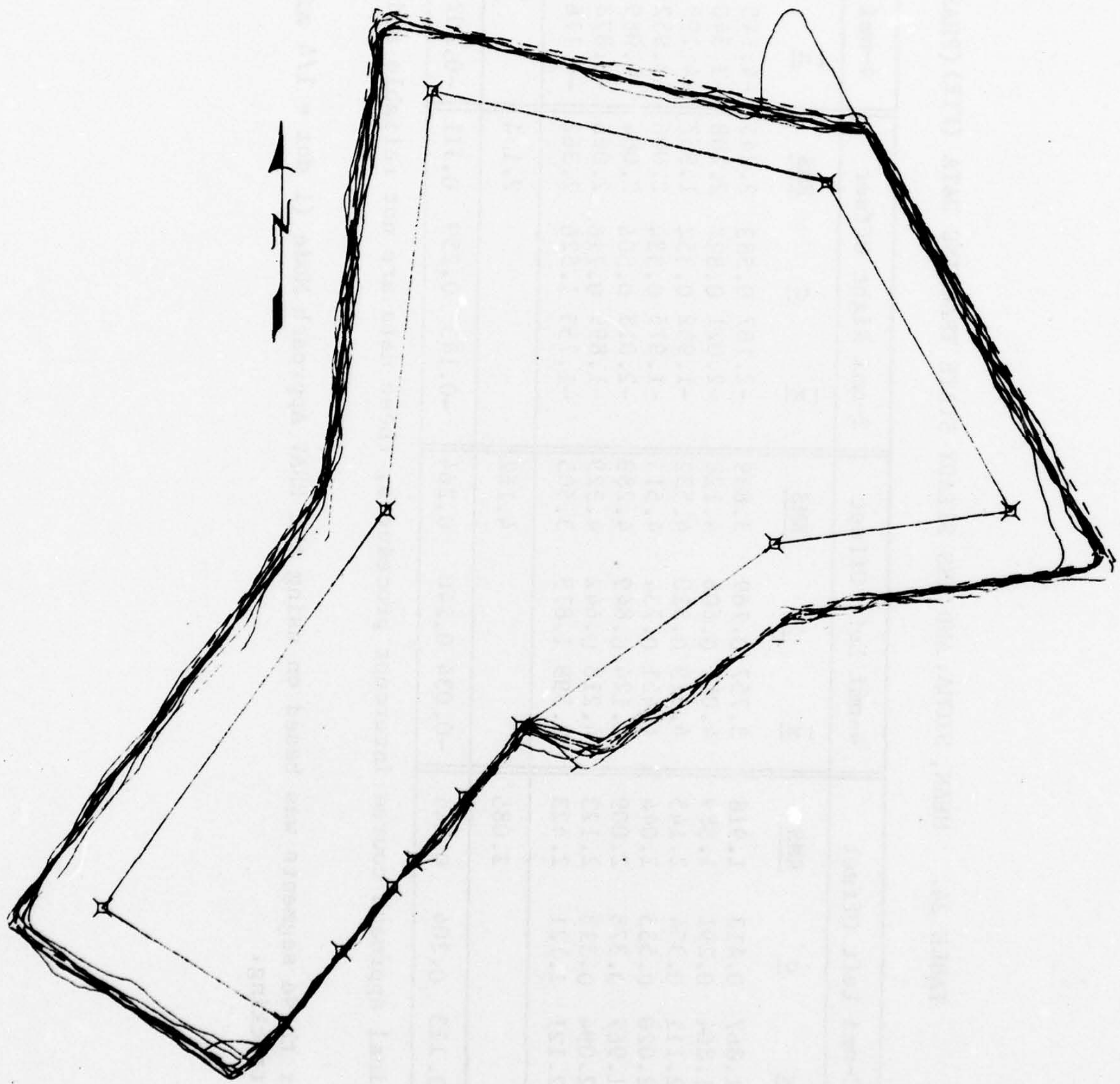


FIGURE 18. COMPOSITE PLOT FOR 4-NMI RIGHT OFFSET (PHASE III)

TABLE 24. MEAN, SIGMA, AND RMS STEADY STATE TRACKING DATA (FTE) (PHASE III)

	2-nmi Left Offset			4-nmi Left Offset			2-nmi Right Offset			4-nmi Right Offset		
Segment	x	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS	$\bar{x}$	σ	RMS
C* - T	1.867	0.413	1.918	3.757	0.769	3.839	-2.167	0.583	2.245	-4.145	0.860	4.236
T - K	1.864	0.291	1.889	4.051	0.606	4.128	-2.021	0.827	2.208	-3.540	1.804	3.996
K - L	2.111	0.354	2.145	4.519	0.310	4.532	-1.932	0.352	1.967	-4.193	0.555	4.235
L - M	2.020	0.535	2.044	4.451	0.734	4.513	-1.975	0.334	2.006	-3.952	0.871	4.058
M - F	1.967	0.378	2.009	4.124	0.849	4.289	-2.018	0.504	2.084	-4.089	1.443	4.351
F - G	2.094	0.318	2.123	4.218	0.642	4.329	-1.899	0.716	2.066	-3.878	1.100	4.032
G - H*	2.121	1.121	2.423	2.599	1.875	3.505	-1.753	1.526	2.362	-4.176	1.348	4.399
Average RMS			2.085			4.162			2.134			4.186
H - J**	-0.113	0.204	0.244	-0.034	0.240	0.264	-0.143	0.259	0.311	-0.102	0.265	0.286

* Due to the final approach course intercept procedures, these data are not reliable and are subject to large errors.

** The data for these segments was based on using the RNAV Approach Mode (1 dot = 1/4 mile) and was center needle tracking.

PROBLEMS INHERENT IN THE USE OF OFFSET TURN ANTICIPATION LOGIC. The TO/FROM logic does allow the pilot to "get into trouble" during the transition at the shallow angle turns (waypoints T, L, and F) in that upon setting the OBS, the CDI needle has little or no movement which results in a lack of time to observe CDI needle motion since the pilot passed the bisector angle before starting the turn.

Figure 19 depicts the geometry at waypoint L, and is presented in order to explain a problem with the TO/FROM logic for right or left offsets. The rules for the TO/FROM logic state that the OBS should be set at a point where the TO/FROM flag is "buried out of view." The CDI distance at this point (assuming that the aircraft is on course) will be approximately the distance of the offset (i.e., 2 or 4 nmi in this study). For a right offset, the pilot must immediately initiate the turn to the next segment (within approximately 8 to 16 seconds after setting the OBS) because the CDI needle either moves very little or not at all and, therefore, the pilot cannot use needle movement as a cue for initiating the turn. The problems stated above contributed to two blunders at waypoint L.

The first occurred during a 2-nmi right offset and resulted in a TSCT error of 2.74 nmi right of course. The pilot commented that the CDI needle did not change when he set the OBS and he became confused. In this case, the CDI needle eventually drifted out to 5 dots left; however, the pilot did not attempt to recenter the needle for approximately 76 seconds. For the second case (a 4-nmi right offset) the pilot also expected the needle to show some movement and became confused. The problem in this case was compounded by the fact that the needle pegged to the left. The pilot stayed on course, waiting for the needle to move, and eventually committed a blunder of 5.73 nmi right of course. The pilot had to be directed to return to course.

In a similar case, another pilot flying a 2-nmi left offset incurred and error of 1.45 nmi left of course while transitioning at waypoint F (29° transition). This occurred as a result of the pilot waiting to observe the CDI needle movement. The pilot initiated the turn when the CDI read 3 nmi right.

These three cases point out a weakness in the TO/FROM OBS set logic and subsequent turn logic that could result in blunders when used under actual IFR conditions. The problem would become even more critical at higher speeds and the logic of OBS SET/TURN would not be useable for shallow angle turns, and would require the implementation of a DTW based logic which would take into account the turn angle and speed of the aircraft.

The problem with the shallow angle turns is further demonstrated by the data in table 25.

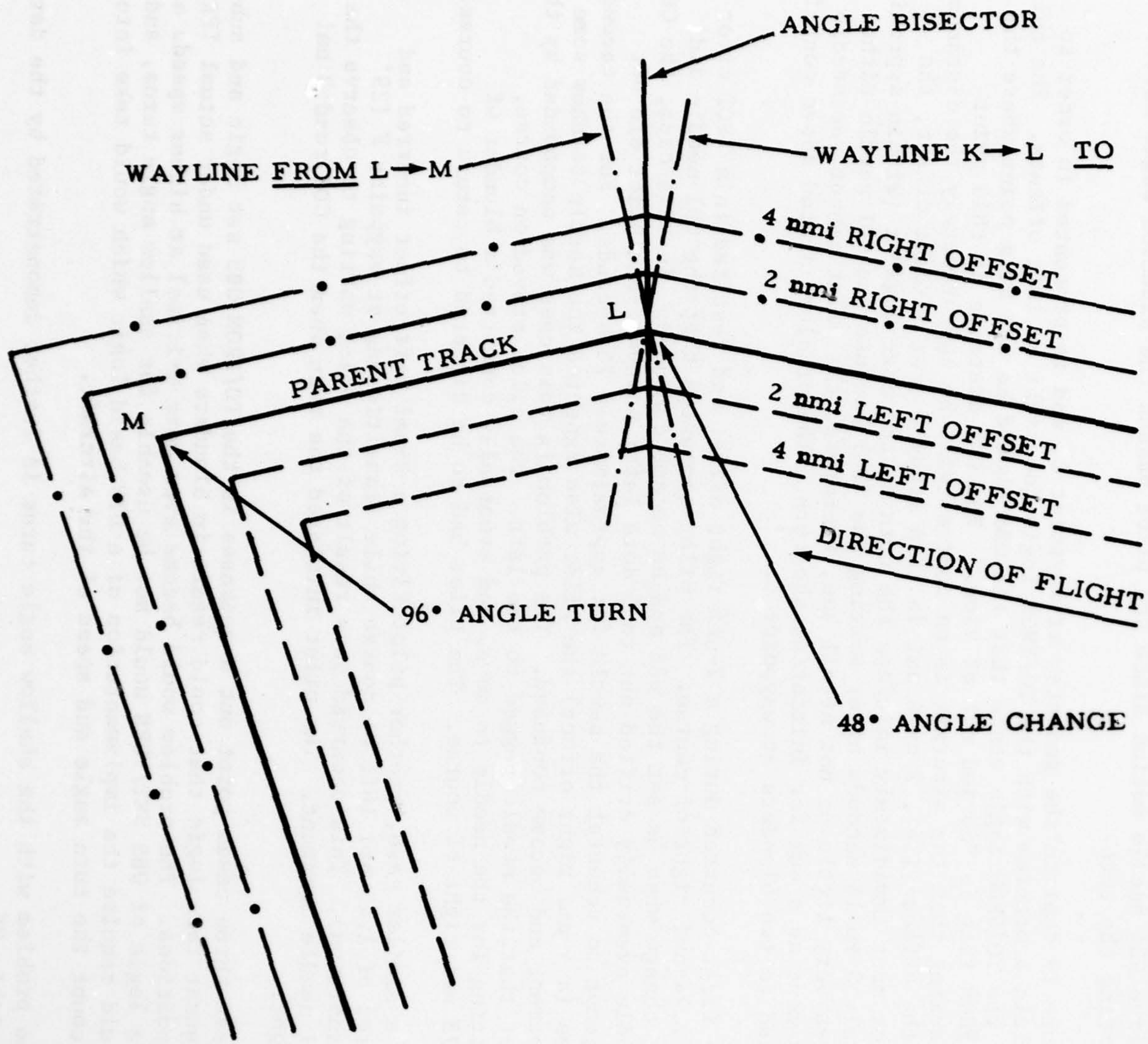


FIGURE 19. DIAGRAM OF TRANSITION AT WAYPOINT L

TABLE 25. ELAPSED TIME BETWEEN OBS SET AND START TURN FOR SHALLOW ANGLE TURNS AT WAYPOINTS L AND F (PHASE III)

Waypoint	Left Offset 2-nmi	Left Offset 4-nmi	Right Offset 2-nmi	Right Offset 4-nmi
L (48°)	41 seconds (2x)	67 seconds (2x)	16 seconds (T/f)	11 seconds (T/f)
F (29°)	11 seconds (T/f)	8 seconds (T/f)	39 seconds (2x)	71 seconds (2x)

2x = Two times distance
T/f = TO/FROM logic

An alternative solution would be to train the pilots to react to the shallow angle turns as quickly as possible, and to start the turn almost immediately after setting the OBS to the next course.

In this study, the steady state TSCT error for offset tracking was the same magnitude as the offset turn data TSCT error. The reason for this is that the turns were made using a set of logic that required the pilot to pay close attention to the CDI needle and the pilots did a reasonable job of transitioning between segments with minimum TSCT error as shown by table 26.

TABLE 26. SUMMARY OF THE OVERALL 2-RMS ($\pm$2.0 NMI WINDOW) TSCT ERRORS (PHASE III)

	2-nmi Left Offset	4-nmi Left Offset	2-nmi Right Offset	4-nmi Right Offset
Steady State Data	1.066	1.294	0.882	0.986
Turn Data	0.966	1.182	0.792	0.956

A potential problem area exists which is directly attributable to the noncentered CDI needle. The pilot's workload is increased with the noncentered CDI needle because he has to fly away from the needle and in other cases he has to fly toward the needle. Under high workload conditions, this could cause confusion which might cause the pilots to fly in the wrong direction. In fact, in this study there were three instances of this wrong needle sensing. One occurred at waypoint T which resulted in an error of 2 nmi right of course. Another occurred at waypoint G and resulted in the pilot flying 4 nmi off course, but parallel to the intended offset course between waypoints G and H. A third case occurred at waypoint F where the pilot sensed the needle wrongly; however, he realized his error and returned to the offset course. In this case the pilot corrected to the needle instead of away from the needle.

RESULTS

1. The "on course" turn anticipation technique recommended by AC 90-45A produced significantly more variability in terms of TSCT than did the University of Illinois/CTI and NAFEC "on course" turn anticipation techniques.

2. Nonprecision approaches, using a single waypoint, analog RNAV system in the approach mode, were sufficiently accurate to be used in a terminal environment.

3. The objective data indicated that for centerline tracking, at speeds of 200 knots or less (TAS), all three turn anticipation techniques were found useable and no blunders were recorded.

4. Offsets of 2-and 4-nmi (left and right of centerline) did not exceed the ± 2-nmi criteria established for steady state tracking capability.

5. The 5-nmi offsets (left and right of centerline) resulted in TSCT and FTE variabilities that exceeded the ± 2-nmi criteria established for steady state tracking capability.

6. During offset transition, the CDI-based turn anticipation technique produced the greatest amount of TSCT variability in shallow turns; whereas, the DTW-based turn anticipation technique produced the greatest TSCT variability in acute turns.

7. For shallow angle turns, the OBS set logic (which used the TO/FROM rule) did not allow enough time for the pilot to observe CDI needle motion and initiate the turn.

8. Based on the computer plots of the routes flown, centerline turn data exhibited less variability in terms of TSCT than did offset turn data.

9. For the 2- and the 4-nmi offsets, the offset turn data was not significantly different from offset steady state data in terms of TSCT variability.

10. Using a noncentered needle to fly offsets increased the pilot's workload because some circumstances required that the pilot fly toward the needle while other circumstances required the pilot to fly away from it.

11. The pilot's attempt to resolve the logic of flying to or from the CDI needle resulted in two operational blunders and one procedural error.

12. A placard detailing the OBS set logic procedures is essential for the pilots to properly implement the correct turn logic while flying offsets.

CONCLUSIONS

Based upon the results of this simulation, the following conclusions are made concerning the useability of a single-waypoint area navigation system in a terminal area environment:

1. For centerline tracking, all three turn anticipation techniques worked, and no blunders were recorded in terms of procedural errors or misinterpretations using any of the techniques.

2. Of the three turn anticipation techniques tested for centerline tracking, the CDI needle method of turn anticipation provides the least variability in terms of TSCT.

3. Procedural turn anticipation techniques based on individual pilot judgment of CDI needle distance (and/or rate of movement) provide no guidelines for advising the pilot when to start his turn. Because of pilot variability, there is a fundamental weakness in the time and distance selection for turn anticipation for both centerline and offset tracking which affects TSCT variability.

4. The magnitude of the offsets that can be flown effectively while using a noncentered needle will be limited by the scale of the CDI instrument's display, its sensitivity, and the speed of the aircraft.

5. None of the turn anticipation techniques tested can provide adequate guidance for transition from an offset condition to the final approach course.

6. An automated turn anticipation method based upon computed DTW distance and turn angle would be superior to the manual methods developed and tested during this simulation for both centerline transitions and for maintaining constant offsets around turns.

7. An automated turn anticipation procedure based on "good" human engineering would eliminate many of the workload-inducing procedures and would provide a consistent application of a set of rules without requiring complex interpretations and decisions on the part of the pilot.

REFERENCES

1. Eldredge, D., Goldberg, B., and Crimbring, W., An Evaluation of Modified RNAV Terminal Procedures Using a Single-Waypoint RNAV System, Federal Aviation Administration, Report No. FAA-RD-78-27, Washington, D. C., April 1978.

2. Jensen, R.S., and Marsh, R. W., Simulator Tests of Pilots Performance in Terminal Area Navigation Operations: Effects of Various Airborne System Characteristics, Federal Aviation Administration, Report No. FAA-RD-76-99, Washington, D. C., May 1976.

APPENDIX

Flight Simulation Technical Note

FSTN No. 6

COMPUTATION OF TURN ANTICIPATION DISTANCE

Douglas A. Elliott
Joseph E. McCall
ANA-241

August 1977

COMPUTATION OF TURN ANTICIPATION DISTANCE

When making a turn from one RNAV course to another at a waypoint, the necessary Turn Anticipation Distance (TAD) at which to initiate a standard-rate turn is developed in the derivations which follow. Expressions without offset and with offset are derived.

Altitude and slant range effects have no influence on these relations, except for the unlikely case of a waypoint so close to a VOR that the RHO value is less than the flight altitude. In normal cases, slant range will cause the apparent waypoint to shift slightly toward the VOR, unless the RNAV computer provides slant range correction. In either case, distance-to-waypoint will read zero when the apparent waypoint is reached, and turns will be made in relation to the apparent waypoint, regardless of altitude.

I. TAD WITHOUT OFFSET:

The following derivation shows the development of a basic expression for Turn Anticipation Distance when no offset is present. A standard-rate turn of 3 deg/sec is assumed, but no allowance is made for time required to establish the turn. This may add approximately 1/4 mile to all distance values.

Turn Anticipation Distance Calculations:

The turn anticipation distance (TAD) is dependent upon airspeed (V), turn angle (ψ), and rate of turn ($\dot{\psi}$). From Figure 1 it can be seen that TAD is expressed by the relation:

$$TAD = R \tan \left|\psi/2\right|$$

Where R is the turn radius. A value for the turn radius can be calculated from the values of airspeed and rate of turn.

$$R\ (NMI) = \frac{57.3\ V\ (KT)}{(3600\ sec/hr)\ \ (\dot{\psi}\ deg/sec)}$$

If we assume a standard rate turn (3°/sec) then:

$$R\ (NMI) = \frac{V\ (KT)}{188.48}$$

Substitution of this relation for R into the equation for TAD provide the relation:

$$TAD = \frac{V\ (KT) \tan \left|\psi/2\right|}{188.48}$$

Table 1 shows the values for TAD (NMI) at airspeeds from 120KT to 200KT and at turn angles from 15° to 120°.

TABLE A-1. TURN ANTICIPATION DISTANCE (NMI)

TURN ANGLE	AIRSPEED (V) KNOTS				
	120	140	160	180	200
15°	.084	.098	.112	.126	.140
30°	.171	.199	.227	.256	.284
45°	.264	.308	.352	.396	.440
60°	.368	.429	.490	.551	.613
75°	.489	.570	.651	.733	.814
90°	.637	.743	.849	.955	1.061
105°	.830	.968	1.106	1.245	1.383
120°	1.103	1.287	1.470	1.654	1.838

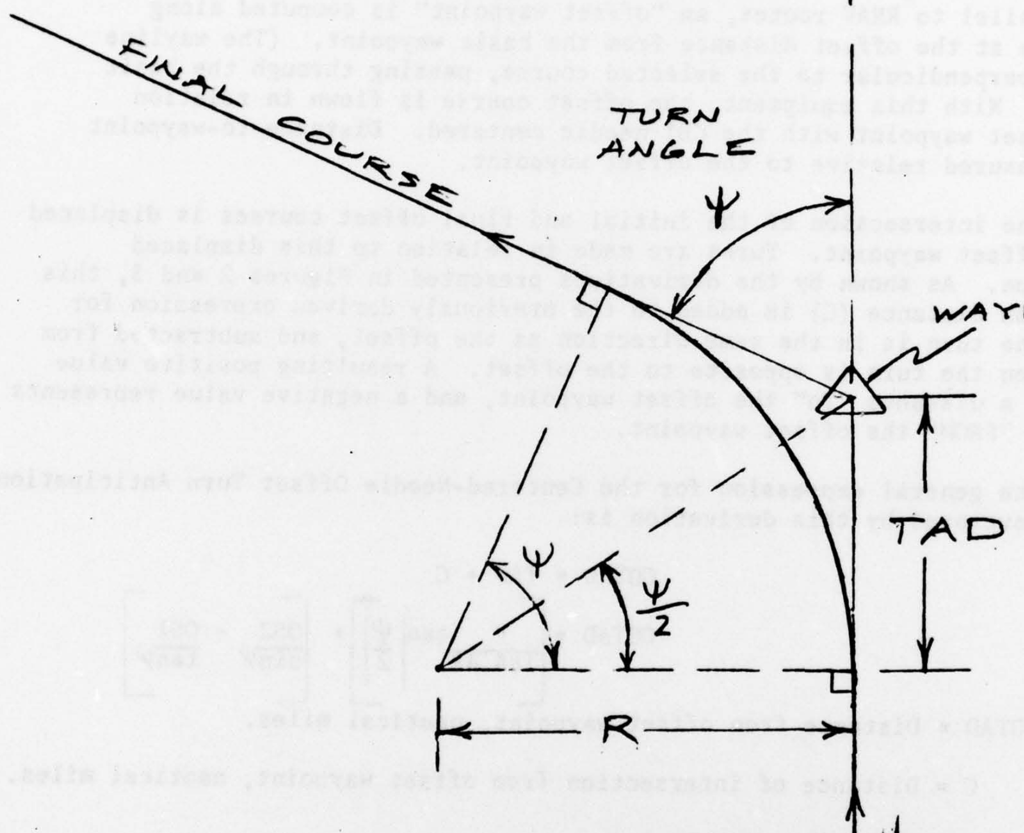


FIGURE A-1. TURN ANTICIPATION WITHOUT OFFSET

II. TURN ANTICIPATION WITH PARALLEL OFFSETS:

A. COTAD (Centered-Needle Offset Turn Anticipation Distance):

When using RNAV equipment that is capable of computing offset coures parallel to RNAV routes, an "offset waypoint" is computed along the wayline at the offset distance from the basic waypoint. (The wayline is a line perpendicular to the selected course, passing through the basic waypoint). With this equipment, the offset course is flown in relation to the offset waypoint with the CDI needle centered. Distance-to-waypoint is also measured relative to the offset waypoint.

The intersection of the initial and final offset courses is displaced from the offset waypoint. Turns are made in relation to this displaced intersection. As shown by the derivations presented in Figures 2 and 3, this intersection distance (C) is added to the previously derived expression for TAD when the turn is in the same direction as the offset, and subtracted from the TAD when the turn is opposite to the offset. A resulting positive value represents a distance "To" the offset waypoint, and a negative value represents a distance "FROM" the offset waypoint.

The general expression for the Centered-Needle Offset Turn Anticipation Distance developed by this derivation is:

$$COTAD = TAD + C$$

$$COTAD = \left[\frac{V}{188.48} \tan\left|\frac{\psi}{2}\right|\right] + \left[\frac{OS2}{\sin\psi} - \frac{OS1}{\tan\psi}\right]$$

Where: COTAD = Distance from offset waypoint, nautical miles.

C = Distance of intersection from offset waypoint, nautical miles.

V = True airspeed, knots.

ψ = Angle of course change.

OS1 = Offset of initial course, nautical miles.

OS2 = Offset of final course, nautical miles.

Positive COTAD represents a "TO" indication.

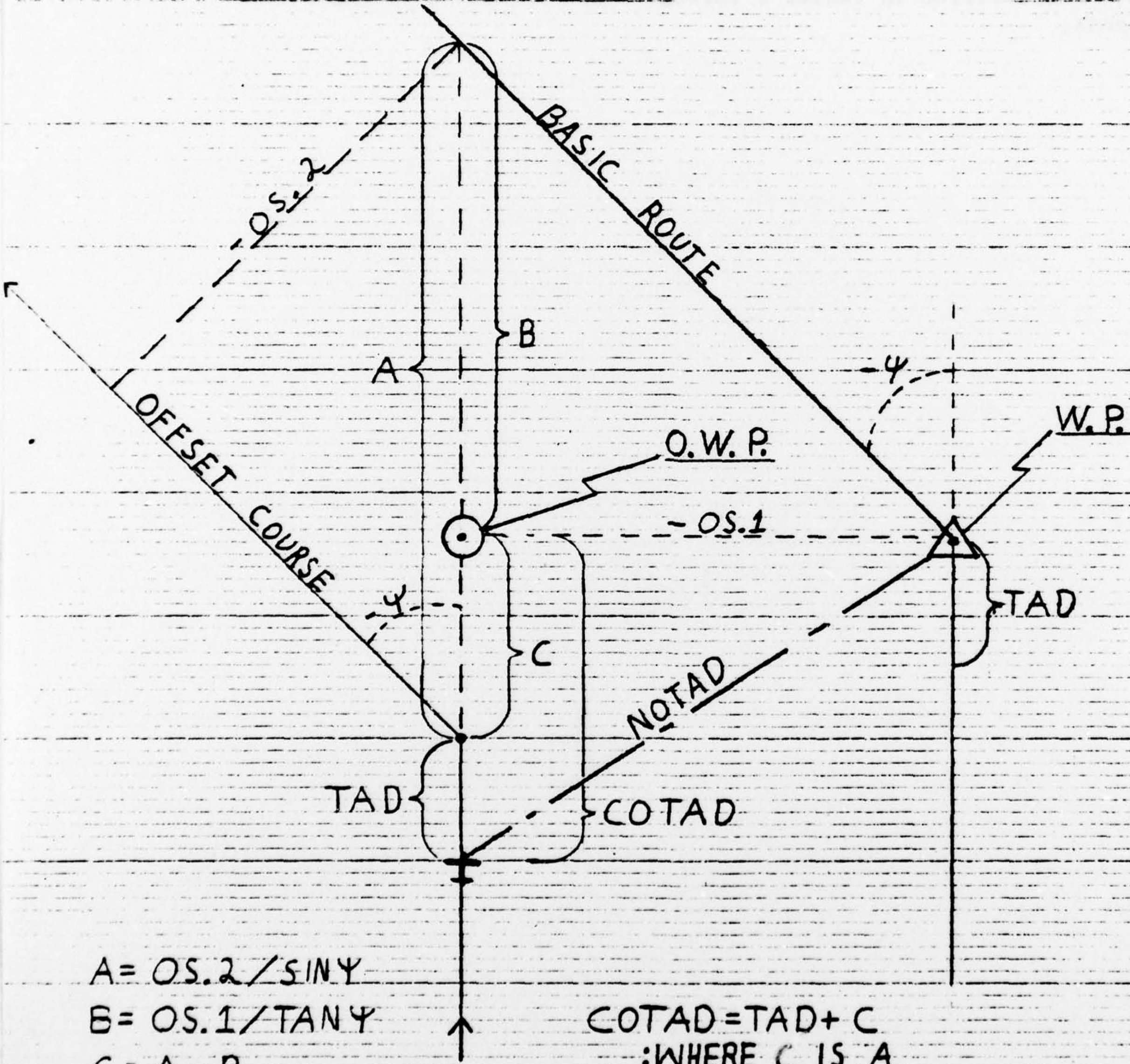
Negative COTAD represents a "FROM" indication.

Positive values are to right for ψ, OS1, OS2.

Negative values are to left for ψ, OS1, OS2.

When ψ and OS1 are both in the same direction (both left or both right), the value of intersection displacement, C, will be positive, and will add to the TAD value, as shown in FIGURE 2.

The computation of NOTAD remains the same as previously developed, except that the value of COTAD is calculated using the above expression for the particular case of equal offsets. The resulting values of COTAD and NOTAD are listed in Tables 2 through 5 for various turn angles and airspeeds.



$A = OS.2 / \sin\Psi$

$B = OS.1 / \tan\Psi$

$C = A - B$
$= (OS.2/\sin\Psi) - (OS.1/\tan\Psi)$

W.P.: WAYPOINT

O.W.P.: OFFSET WAYPOINT

$TAD = (V(KT.)/188.48)\tan|\Psi/2|$

$COTAD = TAD + C$
:WHERE C IS A POSITIVE NO.

$NOTAD = \sqrt{(COTAD)^2 + (OS.1)^2}$

FIGURE A-2. SAME (INSIDE) TURN--LEFT OFFSET, LEFT TURN

When ψ and OS1 are opposite (one left and one right) the value of C will be negative, and will subtract from TAD, as shown in Figure 3.

B. NOTAD (Non-Centered-Needle Offset Turn Anticipation Distance):

With RNAV equipment that has no provision for offset computations, an offset course must be flown with an off-center CDI needle displacement equal to the desired offset. Distance-to-waypoint indications represent distances relative to the basic waypoint.

Although the geometry of the turn remains the same as for the COTAD case, all distance measurements of turn anticipation must be made in relation to the basic waypoint. As shown by the derivations of Figures 2 and 3, NOTAD is simply the hypotenuse of a triangle whose sides are COTAD and OS1. This may be expressed as:

$$\text{NOTAD} = \pm \sqrt{(\text{COTAD})^2 + (\text{OS1})^2}$$

Where the sign of NOTAD is the same as that of COTAD.

NOTAD is "TO" for positive COTAD.

NOTAD is "FROM" for negative COTAD.

C. PARTICULAR CASE OF EQUAL OFFSETS:

When the initial and final offset distances, OS1 and OS2, are the same, the general expression for COTAD reduces to the following relation:

$$\text{COTAD} = \frac{V}{188.48} \tan\left|\frac{\psi}{2}\right| + \text{OS} \tan \frac{\psi}{2}$$

Where: COTAD = Distance from offset waypoint, nautical miles.

V = True airspeed, knots.

ψ = Angle of course change.

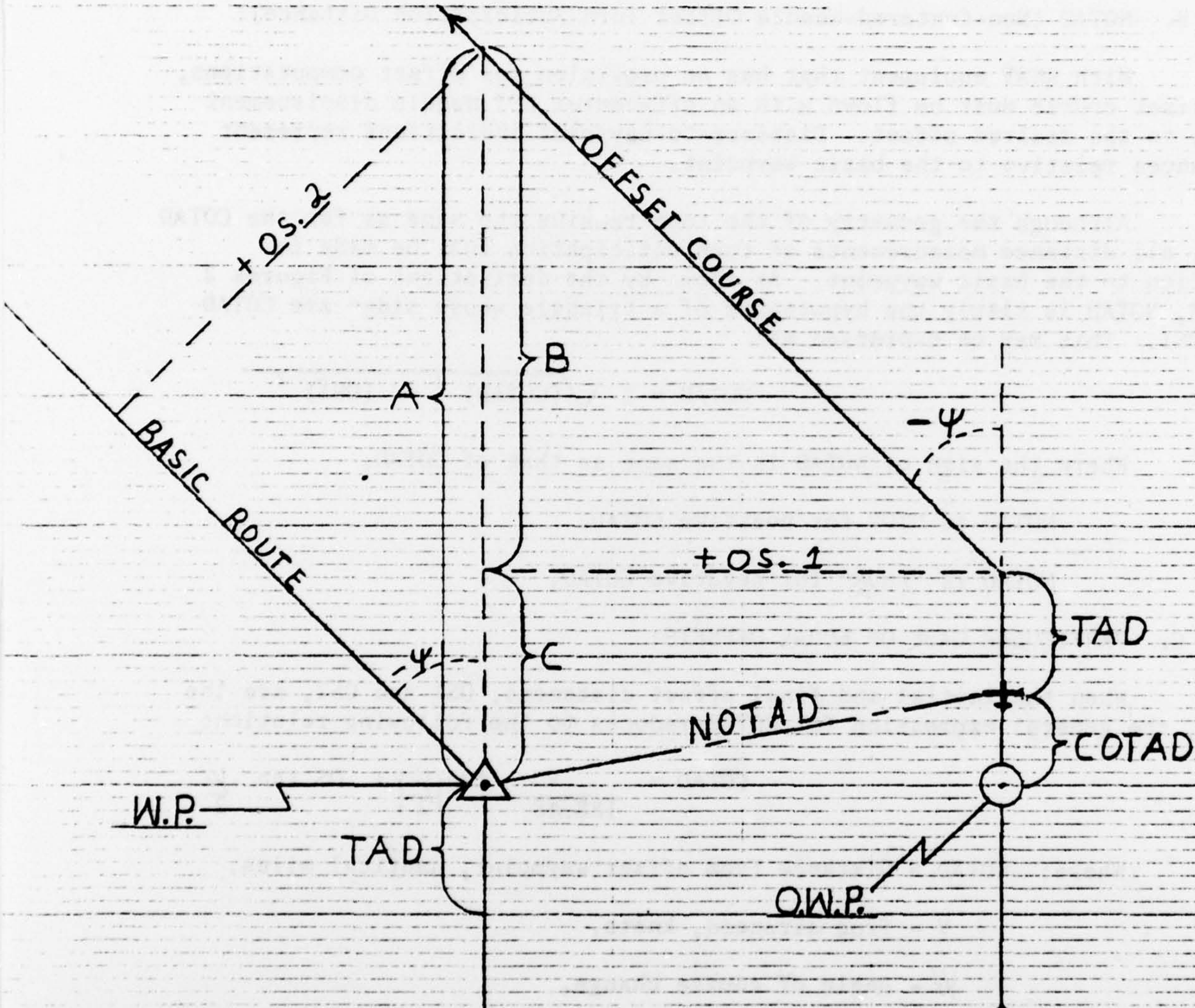
OS = Offset magnitude, nautical miles.

Positive COTAD represents a "TO" indication.

Negative COTAD represents a "FROM" indication.

For ψ and OS, positive values are to the right, negative values to the left.

When ψ and OS are the same direction, C is added to TAD. When opposite, C is subtracted from TAD.



$A = O.S.2 / \sin \Psi$

$B = O.S.1 / \tan \Psi$

$C = A - B$

$\quad = (O.S.2 / \sin \Psi) - (O.S.1 / \tan \Psi)$

W.P. : WAYPOINT

O.W.P. : OFFSET WAYPOINT

$TAD = (V_{(KT.)} / 188.48) \tan |\Psi/2|$

$COTAD = TAD + C$

: WHERE C IS A NEGATIVE NO.

$NOTAD = \sqrt{(COTAD)^2 + (O.S.1)^2}$

FIGURE A-3. OPPOSITE (OUTSIDE) TURN--RIGHT OFFSET, LEFT TURN

TABLE A-2. COTAD, INSIDE (SAME) TURN - RIGHT OFFSET, RIGHT TURN OR LEFT OFFSET, LEFT TURN

120 KNOTS

TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
15	.215	.347	.479	.610	.742	1.400
30	.439	.706	.974	1.242	1.510	2.850
45	.678	1.092	1.506	1.921	2.335	4.406
60	.945	1.522	2.100	2.677	3.254	6.141
75	1.256	2.023	2.790	3.558	4.325	8.162
90	1.637	2.637	3.637	4.637	5.637	10.637
105	2.133	3.436	4.739	6.043	7.346	13.862
120	2.835	4.567	6.299	8.031	9.763	18.423

140 KNOTS

TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
15	.229	.361	.493	.624	.756	1.414
30	.467	.735	1.003	1.271	1.539	2.878
45	.722	1.136	1.550	1.964	2.379	4.450
60	1.006	1.584	2.161	2.738	3.316	6.202
75	1.337	2.105	2.872	3.639	4.407	8.243
90	1.743	2.743	3.743	4.743	5.743	10.743
105	2.271	3.574	4.878	6.181	7.484	14.000
120	3.018	4.751	6.483	8.215	9.947	18.607

160 KNOTS

TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
15	.243	.375	.507	.638	.770	1.428
30	.495	.763	1.031	1.299	1.567	2.907
45	.766	1.180	1.594	2.008	2.423	4.494
60	1.067	1.645	2.222	2.799	3.377	6.264
75	1.419	2.186	2.953	3.721	4.488	8.325
90	1.849	2.849	3.849	4.849	5.849	10.849
105	2.409	3.713	5.016	6.319	7.622	14.138
120	3.202	4.934	6.666	8.398	10.130	18.791

TABLE A-2. COTAD, INSIDE (SAME) TURN - RIGHT OFFSET, RIGHT TURN OR LEFT OFFSET, LEFT TURN (CONTINUED)

				OFFSET (MILES)			
180 KNOTS	TURN ANGLE (DEGREES)	1	2	3	4	5	10
	15	.257	.389	.521	.652	.784	1.442
	30	.524	.792	1.061	1.328	1.596	2.935
	45	.810	1.224	1.638	2.052	2.467	4.538
	60	1.129	1.706	2.283	2.861	3.438	6.325
	75	1.500	2.267	3.035	3.802	4.569	8.406
	90	1.955	2.955	3.955	4.955	5.955	10.955
	105	2.548	3.851	5.154	6.457	7.761	14.277
	120	3.386	5.118	6.850	8.582	10.314	18.974

				OFFSET (MILES)			
200 KNOTS	TURN ANGLE (DEGREES)	1	2	3	4	5	10
	15	.271	.403	.535	.666	.798	1.456
	30	.552	.820	1.088	1.356	1.624	2.964
	45	.854	1.268	1.682	2.096	2.511	4.582
	60	1.190	1.767	2.345	2.922	3.499	6.386
	75	1.581	2.349	3.116	3.883	4.651	8.487
	90	2.061	3.061	4.061	5.061	6.061	11.061
	105	2.686	3.989	5.292	6.596	7.899	14.415
	120	3.570	5.302	7.034	8.766	10.498	19.158

TABLE A-3. COTAD, OUTSIDE (OPPOSITE) TURN - RIGHT OFFSET, LEFT TURN OR LEFT OFFSET, RIGHT TURN

120 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-.048	- .179	- .311	- .443	- .574	- 1.233
	30	-.097	- .365	- .633	- .901	-1.169	- 2.509
	45	-.151	- .565	- .979	-1.393	-1.807	- 3.878
	60	-.210	- .787	-1.365	-1.942	-2.519	- 5.406
	75	-.279	-1.046	-1.813	-2.581	-3.348	- 7.185
	90	-.363	-1.363	-2.363	-3.363	-4.363	- 9.363
	105	-.474	-1.777	-3.080	-4.383	-5.686	-12.203
	120	-.629	-2.361	-4.094	-5.826	-7.558	-16.218

140 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-.034	- .166	- .297	- .429	- .560	- 1.219
	30	-.069	- .337	- .605	- .873	-1.141	- 2.480
	45	-.107	- .521	- .935	-1.349	-1.763	- 3.834
	60	-.149	- .726	-1.303	-1.881	-2.458	- 5.345
	75	-.197	- .965	-1.732	-2.499	-3.267	- 7.103
	90	-.257	-1.257	-2.257	-3.257	-4.257	- 9.257
	105	-.335	-1.639	-2.942	-4.245	-5.548	-12.064
	120	-.446	-2.178	-3.910	-5.642	-7.374	-16.034

160 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-.020	- .152	- .283	- .415	- .547	- 1.205
	30	-.041	- .308	- .576	- .844	-1.112	- 2.452
	45	-.063	- .477	- .891	-1.305	-1.719	- 3.791
	60	-.087	- .665	-1.242	-1.819	-2.397	- 5.283
	75	-.116	- .883	-1.651	-2.418	-3.185	- 7.022
	90	-.151	-1.151	-2.151	-3.151	-4.151	- 9.151
	105	-.197	-1.500	-2.803	-4.107	-5.410	-11.926
	120	-.262	-1.994	-3.726	-5.458	-7.190	-15.850

TABLE A-3. COTAD, OUTSIDE (OPPOSITE) TURN - RIGHT OFFSET, LEFT TURN OR LEFT OFFSET, RIGHT TURN (CONTINUED)

180 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-.006	- .138	- .269	- .401	- .533	- 1.191
	30	-.012	- .280	- .548	- .816	-1.084	- 2.424
	45	-.019	- .433	- .847	-1.261	-1.676	- 3.747
	60	-.026	- .603	-1.181	-1.758	-2.335	- 5.222
	75	-.035	- .802	-1.569	-2.337	-3.104	- 6.941
	90	-.045	-1.045	-2.045	-3.045	-4.045	- 9.045
	105	-.059	-1.362	-2.665	-3.968	-5.272	-11.788
	120	-.078	-1.810	-3.542	-5.274	-7.006	-15.667

200 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	.008	- .124	- .255	- .387	- .519	- 1.177
	30	.016	- .252	- .520	- .788	-1.055	- 2.395
	45	.025	- .389	- .803	-1.217	-1.632	- 3.703
	60	.035	- .542	-1.119	-1.697	-2.274	- 5.161
	75	.047	- .721	-1.488	-2.255	-3.022	- 6.859
	90	.061	- .939	-1.939	-2.939	-3.939	- 8.939
	105	.080	-1.224	-2.527	-3.830	-5.133	-11.650
	120	.106	-1.626	-3.358	-5.090	-6.823	-15.483

TABLE A-4. NOTAD, INSIDE (SAME) TURN - RIGHT OFFSET, RIGHT TURN OR LEFT OFFSET, LEFT TURN

120 KNOTS

TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
15	1.023	2.030	3.038	4.046	5.055	10.098
30	1.092	2.121	3.154	4.188	5.223	10.398
45	1.208	2.279	3.357	4.437	5.518	10.928
60	1.376	2.513	3.662	4.813	5.966	11.735
75	1.605	2.845	4.097	5.353	6.611	12.908
90	1.918	3.309	4.714	6.124	7.535	14.599
105	2.356	3.976	5.609	7.247	8.886	17.092
120	3.006	4.985	6.977	8.972	10.969	20.962

140 KNOTS

TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
15	1.026	2.032	3.040	4.048	5.057	10.100
30	1.104	2.131	3.163	4.197	5.231	10.406
45	1.233	2.300	3.377	4.456	5.537	10.945
60	1.419	2.551	3.697	4.847	5.999	11.767
75	1.670	2.903	4.153	5.408	6.665	12.960
90	2.009	3.394	4.797	6.204	7.614	14.677
105	2.482	4.096	5.726	7.362	9.001	17.205
120	3.180	5.154	7.143	9.137	11.133	21.124

160 KNOTS

TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
15	1.029	2.035	3.042	4.051	5.059	10.101
30	1.116	2.141	3.172	4.206	5.240	10.414
45	1.260	2.322	3.397	4.476	5.556	10.963
60	1.463	2.589	3.733	4.882	6.033	11.800
75	1.736	2.963	4.210	5.463	6.719	13.011
90	2.102	3.481	4.880	6.286	7.695	14.755
105	2.609	4.217	5.845	7.479	9.116	17.317
120	3.355	5.324	7.310	9.302	11.297	21.286

TABLE A-4. NOTAD, INSIDE (SAME) TURN - RIGHT OFFSET, RIGHT TURN OR LEFT OFFSET, LEFT TURN (CONTINUED)

	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
180 KNOTS	15	1.033	2.037	3.045	4.053	5.061	10.103
	30	1.129	2.151	3.182	4.215	5.248	10.422
	45	1.287	2.345	3.418	4.496	5.575	10.981
	60	1.508	2.629	3.770	4.918	6.068	11.832
	75	1.803	3.023	4.267	5.519	6.773	13.064
	90	2.196	3.568	4.964	6.368	7.776	14.833
	105	2.737	4.339	5.964	7.596	9.232	17.431
	120	3.531	5.459	7.478	9.469	11.462	21.448

	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
200 KNOTS	15	1.036	2.040	3.047	4.055	5.063	10.105
	30	1.142	2.162	3.191	4.224	5.257	10.430
	45	1.315	2.368	3.439	4.516	5.595	11.000
	60	1.554	2.669	3.808	4.954	6.103	11.865
	75	1.871	3.085	4.326	5.575	6.829	13.116
	90	2.291	3.656	5.049	6.451	7.857	14.911
	105	2.866	4.462	6.084	7.714	9.348	17.544
	120	3.707	5.667	7.647	9.635	11.628	21.611

TABLE A-5. NOTAD, OUTSIDE (OPPOSITE) TURN - RIGHT OFFSET, LEFT TURN OR LEFT OFFSET, RIGHT TURN

120 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-1.001	-2.008	-3.016	-4.024	-5.033	-10.076
	30	-1.005	-2.033	-3.066	-4.100	-5.135	-10.310
	45	-1.011	-2.078	-3.156	-4.236	-5.317	-10.726
	60	-1.022	-2.149	-3.296	-4.446	-5.599	-11.368
	75	-1.038	-2.257	-3.506	-4.760	-6.017	-12.313
	90	-1.064	-2.421	-3.819	-5.226	-6.636	-13.699
	105	-1.106	-2.675	-4.300	-5.934	-7.572	-15.777
	120	-1.182	-3.095	-5.075	-7.067	-9.062	-19.053

140 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-1.001	-2.007	-3.015	-4.023	-5.031	-10.074
	30	-1.002	-2.028	-3.060	-4.094	-5.128	-10.303
	45	-1.006	-2.067	-3.142	-4.221	-5.302	-10.710
	60	-1.011	-2.128	-3.271	-4.420	-5.571	-11.339
	75	-1.019	-2.221	-3.464	-4.717	-5.973	-12.266
	90	-1.033	-2.362	-3.754	-5.158	-6.567	-13.627
	105	-1.055	-2.585	-4.202	-5.833	-7.469	-15.670
	120	-1.095	-2.957	-4.928	-6.916	-8.909	-18.897

160 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-1.000	-2.006	-3.013	-4.021	-5.030	-10.072
	30	-1.001	-2.024	-3.055	-4.088	-5.122	-10.296
	45	-1.002	-2.056	-3.130	-4.208	-5.287	-10.694
	60	-1.004	-2.108	-3.247	-4.394	-5.545	-11.310
	75	-1.007	-2.186	-3.424	-4.674	-5.928	-12.219
	90	-1.011	-2.308	-3.692	-5.092	-6.499	-13.555
	105	-1.019	-2.500	-4.106	-5.733	-7.367	-15.564
	120	-1.034	-2.824	-4.784	-6.767	-8.758	-18.741

TABLE A-5. NOTAD, OUTSIDE (OPPOSITE) TURN - RIGHT OFFSET, LEFT TURN OR LEFT OFFSET, RIGHT TURN (CONTINUED)

180 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	-1.000	-2.005	-3.012	-4.020	-5.028	-10.071
	30	-1.000	-2.020	-3.050	-4.082	-5.116	-10.290
	45	-1.000	-2.046	-3.117	-4.194	-5.273	-10.679
	60	-1.000	-2.089	-3.224	-4.369	-5.519	-11.281
	75	-1.001	-2.155	-3.386	-4.632	-5.885	-12.173
	90	-1.001	-2.257	-3.631	-5.027	-6.431	-13.484
	105	-1.002	-2.420	-4.013	-5.635	-7.266	-15.458
	120	-1.003	-2.698	-4.642	-6.619	-8.607	-18.586

200 KNOTS	TURN ANGLE (DEGREES)	OFFSET (MILES) 1	2	3	4	5	10
	15	1.000	-2.004	-3.011	-4.019	-5.027	-10.069
	30	1.000	-2.016	-3.045	-4.077	-5.110	-10.283
	45	1.000	-2.037	-3.106	-4.181	-5.259	-10.663
	60	1.001	-2.072	-3.202	-4.345	-5.493	-11.253
	75	1.001	-2.126	-3.349	-4.592	-5.843	-12.126
	90	1.002	-2.209	-3.572	-4.964	-6.365	-13.413
	105	1.003	-2.345	-3.922	-5.538	-7.166	-15.353
	120	1.006	-2.578	-4.503	-6.474	-8.459	-18.431